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Distribution and mechanism of Neogene to present-day vertical axis rotations, Pacific-Australian plate boundary zone, South Island, New Zealand

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Abstract. Remarkably little knowledge exists about mechanisms of vertical axis rotation in continental crust. Steeply dipping basement rocks in South Island, New Zealand, provide an opportunity to map the distribution of rotations across the Pacific-Australian plate boundary zone, and to delineate boundaries of rotated blocks in unusual detail. We synthesize new structural data with new and existing paleomagnetic data, with geodetic data, and with patterns of Neogene-Quaternary faulting in the strike-slip Marlborough fault system. For the past 20 m.y., vertical axis rotations have been hinged about two crustal-scale boundaries near the east coast. The NE hinge accommodated ~50° of early-middle Miocene clockwise rotation, which caused deformation of the eastern ends of the Alpine-Wairau and Clarence strike-slip faults. The SW hinge has accommodated a further 30°-50° of finite clockwise rotation since ~4 Ma and deflects active fault traces. The locus of rotation has shifted southwestward astride a subduction margin that is lengthening in that direction. Rotating rocks are pinned to the south against a locked collision zone where the continental Chatham Rise impinges against the margin. Slip on inland strike-slip faults is transformed seaward across a zone of fault termination into rigid body rotation of a large continental block that has been thrust eastward over the downgoing subducted slab of the Pacific plate. The rotation mechanism is a "migrating hinge," which resembles a flexed telephone book. Strike-slip faults are translated through a brecciated hinge region that does not coincide with a fixed material line in the rock.

Introduction

Fault block rotations about vertical axes are a fundamental mechanism of continental deformation [*McKenzie and Jackson*, 1983, 1986; *Taymaz et al.*, 1991]. Vertical axis rotation is a first-order tectonic process in zones of transpressive deformation and strike-slip faulting such as the western Transverse Ranges of California [*Jackson and Molnar*, 1990; *Luyendyk*, 1991; *Molnar and Gipson*, 1994; *Dickinson*, 1996] and the northeastern part of the South Island of New Zealand [e.g., *Freund*, 1971; *Merzer and Freund*, 1974; *Lamb*, 1988; *Walcott*, 1989; *Roberts*, 1992, 1995; *Vickery and Lamb*, 1995]. In both regions, paleomagnetic studies indicate that large (locally >100°) rotations occurred during the Neogene, and geodetic data indicate that both areas continue to rotate today. Although paleomagnetic and geodetic studies can constrain magnitudes and rates of rotation through time, they tell us little about structural processes that cause (or allow) one crustal block to rotate with respect to another, about the dimensions and shapes of these blocks, or about the details of the nature of their boundaries.

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Kinematic models have been proposed to explain the mechanisms by which rotation is imparted to rigid blocks [e.g., *Ron et al.*, 1984; *Lamb*, 1987; *Garfunkel*, 1989]. Such models define relationships between block orientation, block rotation, slip between blocks, and displacement of the boundaries of the deforming zone in which the blocks are embedded (Figure 1). Some models attribute rotation to frictional tractions that act on blocks in a strong upper crust [e.g., *Garfunkel*, 1989], while others consider rotation to be a passive response of weakly-coupled crustal blocks to underlying continuous deformation [e.g., *Lamb*, 1987]. Regardless of theoretical differences in inferred dynamics, mechanisms of actual crustal rotations are still not well documented, and several important kinematic problems inherent to block rotation models remain poorly explained. For example, what kind of internal deformation of crustal blocks avoids the large gaps (or overlaps) that appear along rigid block boundaries in all slat- or domino-style rotation models? Only at the ends of the blocks does deformation occur as a result of relative rotation of the blocks, therefore structural data from such regions are critical to understanding the mechanism of block rotation. Even if faults are nearly frictionless, finite block rotations of >25°-60° are theoretically impossible to obtain by slip on a single set of faults [*Nur et al.*, 1986; *Garfunkel*, 1989]. Where, in nature, are these multiple sets of variably rotated, large finite slip faults? Any given fault block rotation geometry is self-destructing or is kinematically unstable. If plate motions are, by comparison, continuous and slowly changing, then how do large finite rotations accrue in plate boundary zones? What is the depth and nature of the lower boundaries of rotated fault blocks? At convergent margins, how do the kinematics of subduction or the presence of underlying oceanic slabs affect rotation of upper-plate crustal faults? In this paper, we argue that a one-sided migrating hinge model (Figure 1d) explains the pattern of faulting and rotation in part of the plate boundary zone in New Zealand.

In this study, rotational deformation in the strike-slip Marlborough fault system, South Island, New Zealand (Figure 2), is considered. Dextral slip across the main strand of the Alpine fault can account for only ~480 km of the total ~800 km of Cenozoic slip that finite plate reconstructions [*Stock and Molnar*, 1987; *Sutherland*, 1995] require through New Zealand. The northern (Wairau) part of the Alpine fault, together with the major strands of the Marlborough fault system, can account for no more than ~200 km of slip [*Freund*, 1971; *Silberling et al.*, 1988; *Mazengarb et al.*, 1993; *Little and Jones*, 1997]. One can therefore infer that some displacement has been overlooked. Because paleomagnetic data in New Zealand have largely been obtained from mid-Miocene or younger strata, and are spatially scattered, large gaps remain in our knowledge of the distribution of total Cenozoic finite rotation. More complete data on finite rotations have bearing on the age and origin of the bend of South Island basement terranes, which become NE-striking in proximity to the Alpine fault (Figure 3) and on the magnitude of distributed Cenozoic dextral slip that contributes to this apparent bending [e.g., *Walcott et al.*, 1981; *Kamp,* 1987a]. If a kinematic mechanism for rotation can be identified, then observed vertical axis rotations of blocks in a deforming zone can be used to estimate total slip across that zone [e.g., *Dickinson,* 1996].

In this paper, we present new data of three types. First, we report paleomagnetic data from a new site in late Miocene rocks. Second, we present a map and structural data that define the regional structure of the Torlesse terrane which occurs as basement beneath the paleomagnetically sampled Cenozoic cover strata in northeastern South Island. Importantly, the Torlesse has a near-vertical bedding fabric which provides a remarkable (perhaps unique) opportunity to map vertical axis rotations of crustal blocks and to define their boundaries. Together, these data can be used to infer the distribution of finite vertical axis rotation across the deforming region. Third, we discuss aspects of the Neogene-Quaternary tectonics of major strands of the Marlborough fault system in relation to past and ongoing crustal rotations in this region.

Tectonic Setting of the Marlborough Fault System

New Zealand straddles an actively deforming plate boundary zone between the Australian and Pacific plates (Figure 2). Across Cook Strait, between the two islands of New Zealand, the strike and character of this zone changes. To the east of the North Island, oceanic crust of the Pacific plate is being subducted westward beneath the NNE striking continental edge of the Hikurangi margin. Southward from East Cape, plate convergence is increasingly oblique to this margin [*DeMets et al.*, 1990, 1994]. On the South Island, westward relative motion of the Pacific plate is transferred onto ENE to NE striking dextral strike-slip faults of the Marlborough fault system on the overriding continental plate. Beneath the Marlborough fault system, Benioff zone seismicity continues to depths >250 km [*Anderson et al.,* 1993]. The subduction trench (Hikurangi Trough) terminates near Kaikoura, where the Pacific plate includes the Chatham Rise, a buoyant ridge of continental rocks that is ~23-26 km in thickness [*Lewis and Pettinga*, 1993; *Eberhart-Phillips and Reyners,* 1997]. Geodetic data imply that the southern end of the subduction zone is locked [*Walcott*, 1978a; *Bibby*, 1981], and geologic data suggest that it has propagated southward during the late Neogene [*Anderson et al.*, 1993; *Reyners and Cowan*, 1993; *Nicol et al.*, 1994]. The Marlborough fault system, which is ~200 km in width, links the west dipping Hikurangi subduction zone to the east dipping, dextral-reverse Alpine fault [*Norris et al.*, 1990]. Since earliest Miocene inception of this subduction-to-transform margin in northern South Island [*Cooper et al.*, 1987; *Rait et al.*, 1991], the Euler pole has migrated southward, and relative motion across the transcurrent Marlborough fault system has become increasingly convergent [*Walcott*, 1978b; *Little*, 1995]. Today, the active faults in this system are chiefly dextral, but net reverse slip has caused uplift on the NW sides of these faults [*Lensen*, 1963; *Lamb and Bibby*, 1989; *Van Dissen and Yeats*, 1991; *Little et al.,* in press]. Modeling of geodetic data suggests that these faults and the contiguous Hikurangi margin are currently rotating relative to the Pacific plate at rates of ~3°-8°/m.y. in coastal areas of NE South Island [*Lamb and Bibby*, 1989; *Walcott*, 1989].

Neogene vertical axis rotations are well documented in the Hikurangi forearc of North Island, New Zealand. Because the Australian plate has rotated relative to north at ~1°/m.y. since the Miocene [*Idnurm*, 1985], ~20°-25° of the observed clockwise rotation can be attributed to apparent polar wander since earliest Miocene time. Paleomagnetic data from Miocene-Pliocene rocks of the North Island indicate that much of the Hikurangi margin has rotated a further 35°±10° clockwise (relative to the Australian plate) at a rate of ~1°/m.y. between 24-4 Ma, increasing to ~6°-7°/m.y. after 4 Ma due to the added velocity resulting from back arc extension across the Taupo Volcanic Zone [*Wright and Walcott,* 1986; *Walcott*, 1989; *Beanland*, 1995]. Plate reconstructions suggest that this rotation has caused the Hikurangi margin to change from an original early Miocene trend of WNW to its current trend of NNE [*Walcott*, 1984a; *Lamb and Bibby*, 1989].

On the South Island, paleomagnetic data are chiefly limited to Neogene strata that overlie poorly mapped and little understood Mesozoic basement rocks (Torlesse terrane). These data indicate temporally and spatially variable clockwise vertical axis rotations of crustal blocks across the region (Figure 3). Large (>100°) clockwise vertical axis rotations affected early Miocene rocks north of Kaikoura from 18 to 8 Ma (Figure 3) [*Mumme and Walcott*, 1985; *Vickery and Lamb*, 1995]. Rotations of 20°-40° are recorded in rocks as young as 4 Ma across much of coastal Marlborough to the north of Kekerengu [*Walcott et al.*, 1981; *Roberts*, 1992, 1995], and Pliocene rocks at several sites SW of Kekerengu are unrotated [*Roberts*, 1992; *Vickery*, 1994]. The dimensions of these rotated domains are poorly constrained by structural data, as is the nature of their boundaries. The Marlborough fault system must contain, at some scale, a hinge zone that separates the rapidly rotating Hikurangi margin to the north from unrotated rocks on the Pacific plate to the south. Although its location has been the topic of speculation [e.g., *Walcott*, 1984a; *Roberts*, 1992], such a crustal discontinuity has never been mapped or identified in New Zealand.

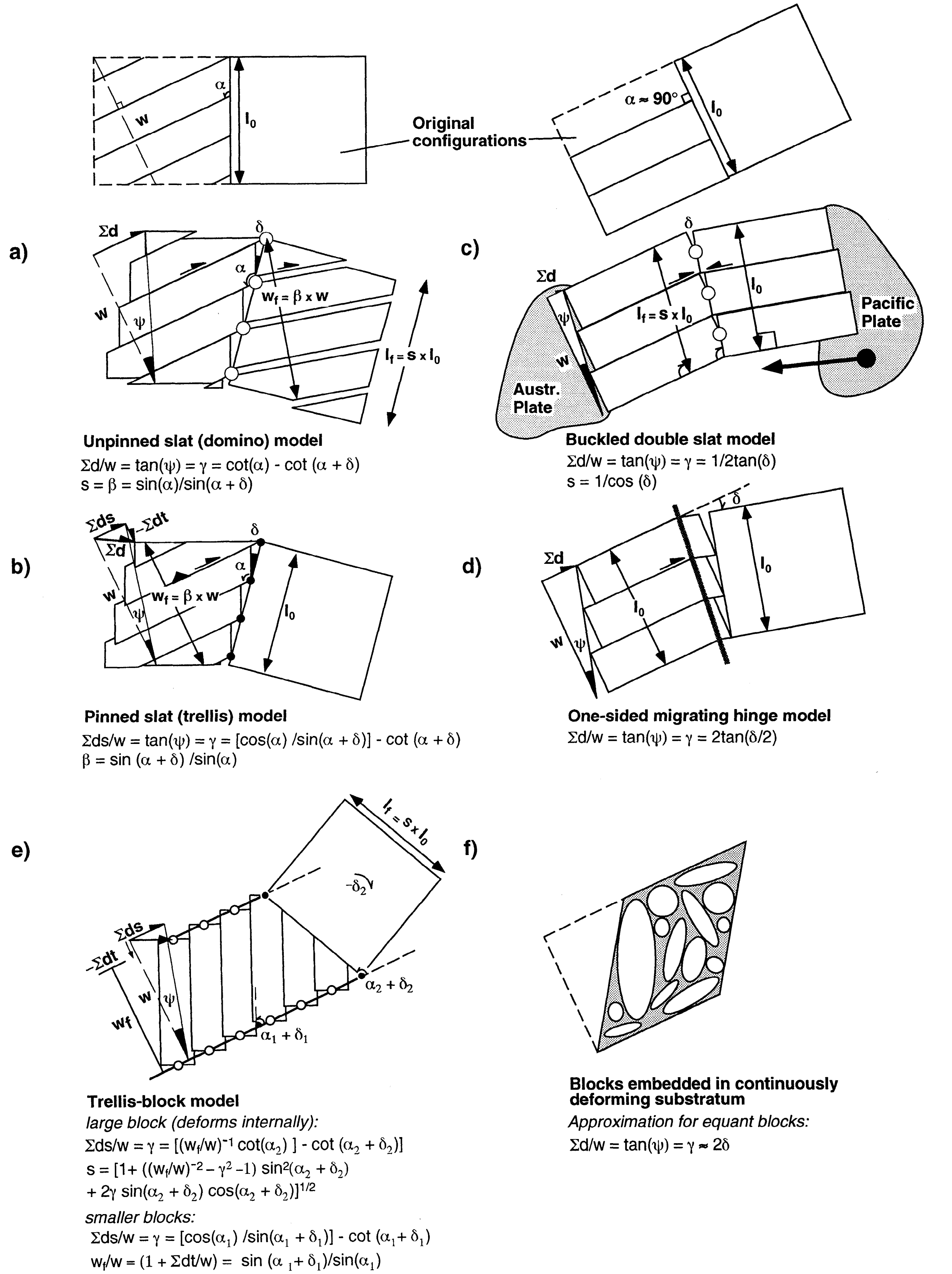


Figure 1. Kinematic models that have been suggested to explain rigid-body rotations of fault blocks in zones of strike-slip faulting. Stippled region is the clockwise-rotated domain. Variables are: l_o, original length of rotation boundary; l_f, final length of rotation boundary; w, original width of strike-slip fault zone; w_f, final width of strike-slip fault zone; s, stretching factor parallel to rotation boundary; β, stretching factor parallel to dip of faults; α, original angle between strike-slip faults and rotation boundary; δ, vertical axis rotation; ψ, angular shear; γ, finite shear strain = $\tan(\psi)$; Σd, cumulative fault slip; Σds, cumulative strike-slip component; Σdt, cumulative fault-orthogonal slip component. See text for further explanation.

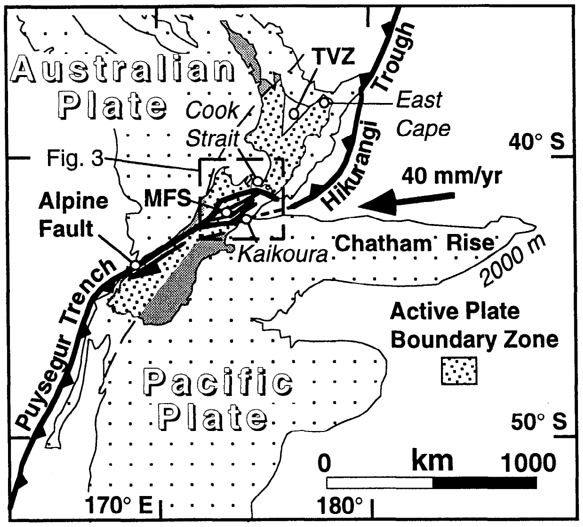


Figure 2. Present-day tectonic setting of New Zealand on the obliquely-convergent boundary between the Pacific and Australian plates. Local plate motion vector from *DeMets et al.* [1990, 1994]. The Marlborough fault system (MFS) links the Alpine fault to the Hikurangi subduction margin. "TVZ" is Taupo Volcanic Zone.

Fuchsia Creek Paleomagnetic Locality

A suite of 48 cores of claystone, mudstone, and siltstone were drilled at nine sites (conventional 25 mm diameter paleomagnetic samples) across a ~290-m-thick section of terrestrial strata that is exposed in the bed of Fuchsia Creek in the central Awatere Valley (Figure 4, location "FC"). The unnamed sequence (MPal unit) has been described by *Maxwell* [1990], *Browne* [1995], and *Jones* [1995] and consists of 1 to 3-m-thick beds of grey-green claystone and mudstone and thinner lenses of sandstone, conglomerate, and minor lignite. The rocks conformably overlie fossiliferous marine strata of the Upton Formation that have a late Miocene age of 7.4-6.0 Ma (late Tongaporutuan to possibly earliest Kapitean stages of the New Zealand time scale) [*Roberts and Wilson,* 1992; *Roberts et al.,* 1994; *Browne,* 1995]. The section is truncated to the north by the active Awatere fault, and is dextrally offset, to the south, by an inactive high-angle fault. We infer that the terrestrial strata were deposited during a late Miocene (Kapitean) low-stand in sea level that has been recognized and well-dated magnetostratigraphically at 5.9-5.2 Ma at several other sites in the otherwise marine Miocene-Pliocene Awatere basin [*Roberts et al.,* 1994]. The timing of this eustatic event corresponds with the timing of the Messinian salinity crisis in the Mediterranean [*Roberts et al.*, 1994].

Forty-four samples were subjected to stepwise thermal demagnetization at 20°, 80°, 120°, 160°, 200°, 240°, 280°, 320°, 360°, 400°, 450°, 500°, 550°, 570°, and 580°C. Twenty-five of these samples (chiefly claystone) from six sites at Fuchsia Creek displayed stable magnetizations, after removal of a low-temperature, normal polarity, secondary remanence component (Figure 5a). All of the samples have reverse polarity characteristic remanence directions (Figure 5a), except for those from the uppermost site which display normal polarity. There are too few normal polarity sites to enable a statistically meaningful reversal test; however, the thickness of the sampled section and the presence of a geomagnetic field reversal within the section indicates that the samples represent a time interval that is sufficiently long to average the effects of geomagnetic secular variation. After correction for the mean strike and dip of the uniformly tilted sequence (235, 24 NW $\alpha_{95} = 7°$, $n = 12$), a locality-mean direction was determined ($D = 180.1°$; $I = 58.7°$; $\alpha_{95} = 10.6°$; Figure 5b). The locality-mean direction is consistent with that expected for an axial dipole geomagnetic field with no subsequent tectonic rotation.

This result provides a paleomagnetic constraint on the westward limit of the Northern Marlborough Domain [*Lamb*, 1988], which is a large crustal block that lies between the Wairau and Kekerengu faults which has rotated 20°-40° clockwise since 4 Ma [*Roberts*, 1992, 1995]. Together with results at three early Pliocene sites farther to the south [*Roberts,* 1992; *Vickery,* 1994], near Kekerengu, this result suggests that a southwestern region in the Marlborough fault system has not rotated clockwise, relative to the Pacific plate, in the late Neogene (Figure 3).

Basement Structure and Paleomagnetic Rotations

Structural Fabric of Torlesse Terrane in Northeastern South Island

Faulted and gently folded, mostly marine late Miocene-Pliocene rocks of the Awatere basin are widespread between the coastal towns of Blenheim and Ward [*Roberts and Wilson,* 1992] (Figure 3). These strata unconformably overlie a strongly-deformed, subduction-accretion complex that contains Late Jurassic to Early Cretaceous fossils: the Pahau subterrane of the Torlesse terrane. The fault-imbricated Pahau subterrane consists chiefly of turbiditic sandstone and argillite, with minor basalt, chert, green tuff, red siltstone, limestone, and pebble-cobble diamictite that was derived from these lithologies. The Pahau subterrane makes up the basement for most of the NE South Island, and it is faulted to the west against the arcuate Esk Head subterrane, which is an older assemblage within the Torlesse terrane [*MacKinnon*, 1983; *Bishop et al.*, 1985; *Silberling et al.*, 1988; *Bradshaw*, 1989].

At the outcrop scale, Pahau rocks have a complex, tightly folded structure. The basic sequence and style of deformation is similar throughout the study region (Figure 4). Similar structural sequences have been described at many other locations in the Torlesse, where they have been attributed to progressive dewatering, subduction, and thrust imbrication (underplating) in the late Mesozoic [*Spörli*, 1978; *Ward and Spörli*, 1978; *Barnes and Korsch*, 1990; *George*, 1990; *Korsch and Morris*, 1990]. Early brittle-ductile structures reflect bedding-parallel extension of sandstone beds and bedding-parallel shear that is focused into weaker argillite rich units. Broken formations, one to tens of meters in thickness, may contain a shear-related scaly foliation that lies subparallel to bedding. Abundant tight-isoclinal folds (F_1) generally deform this fabric about hinges that originally trended ENE to NE. Some F_1 folds have wavelengths of ~1 km and axial traces up to 10 km in length (e.g., Figure 4, location "TP"). These folds are uncleaved and have short forelimbs that are truncated against décollement surfaces (probably thrust faults). Facing directions in the steeply tilted turbidite sequences are dominated by N younging beds. Dominance of NW or N younging beds suggests stratal repetition by SE verging thrust faults. The thrust imbricates were later back rotated to near-vertical dips, causing the F_1 hinges to become steeply plunging (Figures 6d and 6e).

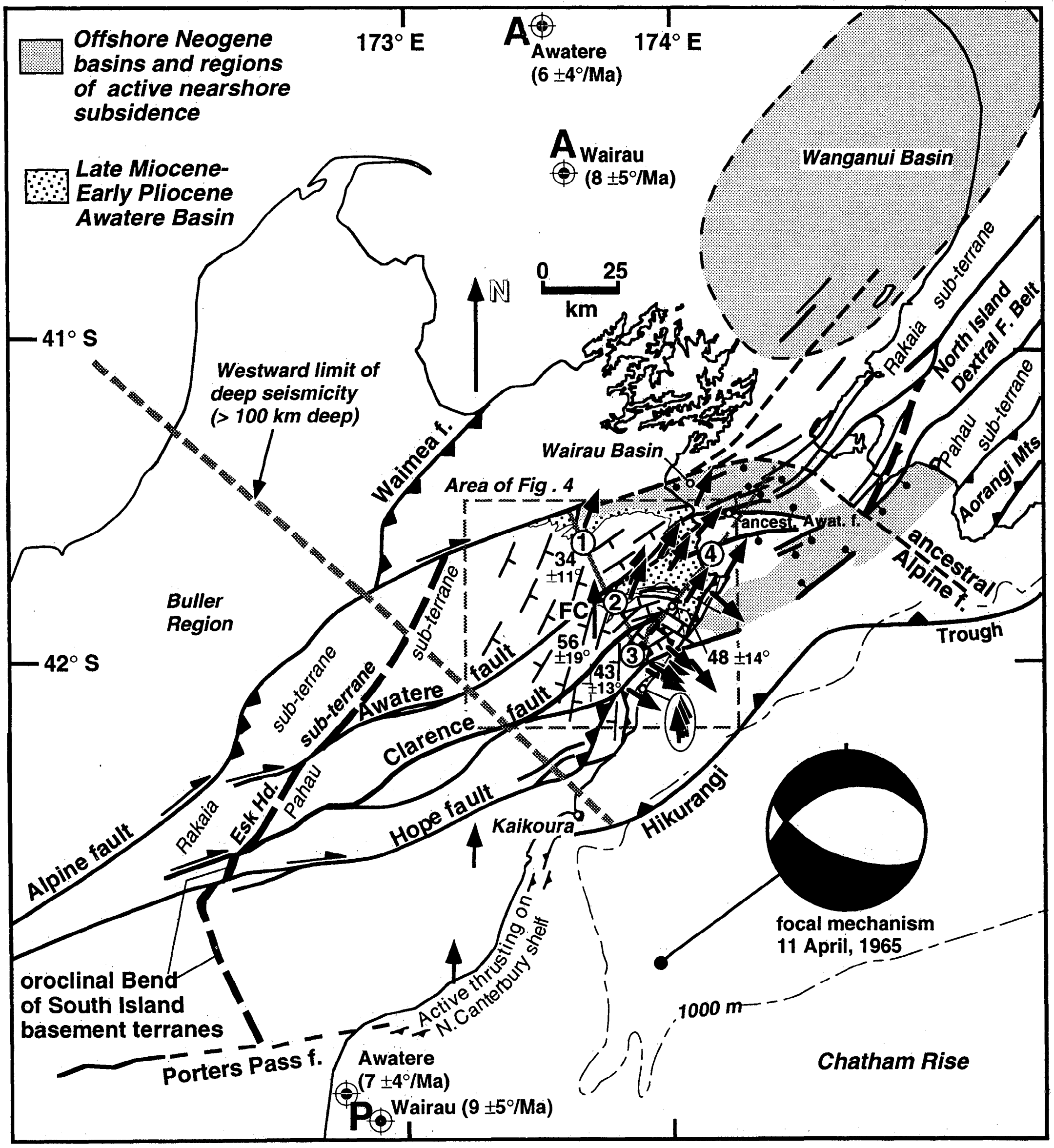


Figure 3. Tectonic map of northeastern South Island, Cook Strait, and southern North Island, New Zealand. Arrows denote paleomagnetic rotations relative to the Pacific plate (from *Roberts* [1992]; *Vickery and Lamb* [1995; this study]). FC is Fuchsia Creek paleomagnetic locality (this study). Strike and dip symbols are mean attitudes of Torlesse bedding fabric. Circled numbers 1-4 refer to rotation boundaries. The focal mechanism for a normal faulting earthquake on Chatham Rise and the westward limit of deep seismicity on the Pacific plate are from *Anderson et al.* [1993]. Geodetically estimated rotation poles and angular rotation rates for the Awatere and Wairau faults, relative to Australian (A) and Pacific (P) plates are from *Lamb* [1988]. Fault traces and geology are from *Lensen* [1963], *Grapes and Wellman* [1987], *Silberling et al.* [1988], *Carter et al.* [1988], *Waters* [1988], *Van Dissen and Yeats* [1991], *Lewis and Pettinga* [1993], *Barnes* [1994], *Beanland* [1995], and *Little* [1995; unpublished mapping, 1992-1996]. See text and Figure 4 for explanations.

Renewed faulting, folding and prehnite-pumpellyite-facies regional metamorphism accompanied later stages of crustal shortening [e.g., *George*, 1990]. The last deformation phase typically involved pervasive faulting, bedding plane shear, jointing, cataclasis and brecciation at almost all scales. At least partially Cenozoic, this brittle overprint imparts a shattered appearance to many outcrops.

In this study, the fabric of Torlesse rocks is used as a marker for vertical axis rotations. Despite the complexity of its deformation at outcrop scale, tightly folded bedding in the Torlesse terrane defines a mean (statistical) fabric that is remarkably planar, consistent, and steeply dipping at the kilometer scale. Throughout most of inland Marlborough, mean bedding strikes to the NNE, with steep dips to the SE and mainly NW facing (Figure 4). Because the planar fabric dips everywhere within ~20° of vertical, it is ideally suited for tracking changes in vertical axis rotation. If Cenozoic paleomagnetically determined vertical axis rotations are not superficial, then differences between sites should be expressed by corresponding changes in the mean strike of the Torlesse

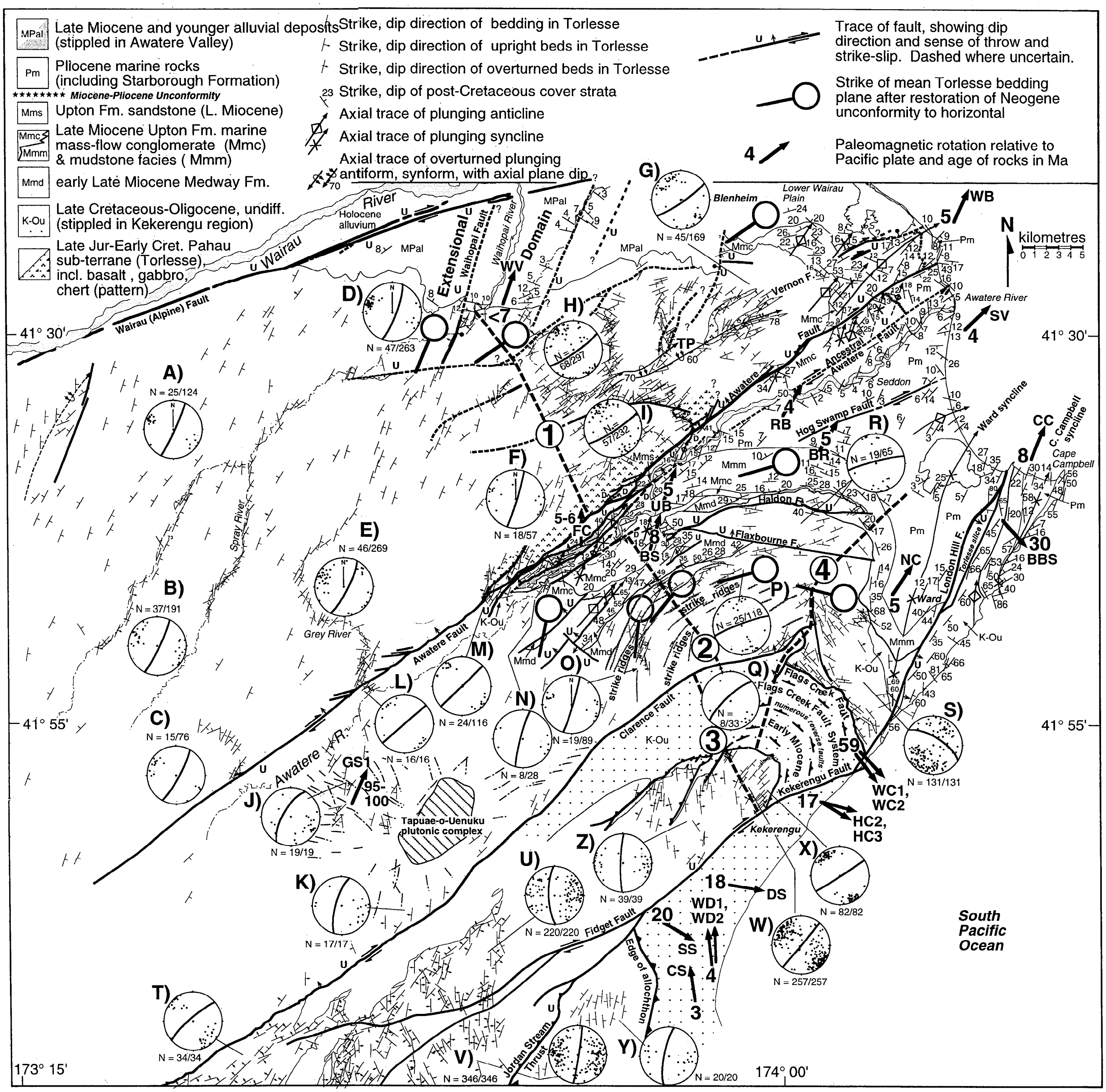


Figure 4. Simplified structural map of NE South Island, New Zealand. Compiled from *Russel* [1959], *Lensen* [1963], *Prebble* [1976], *R.J. Korsch* (unpublished data, 1983), *Ritchie* [1986], *Waters* [1988], *Melhuish* [1988], *Kirker* [1989], *Harker* [1989], *Maxwell* [1990], *Roberts and Wilson* [1992], *Browne* [1992a, b], *Reay* [1993], *Vickery* [1994], *Lowry* [1995], *Lock* [1995], *Jones* [1995], *T.A. Little* (unpublished data 1992-1996), and *Crampton and Laird* [in press]. FC is Fuchsia Creek paleomagnetic locality (paleomagnetic locality abbreviations are in Table 2 and Figure 7); TP is fold trace mapped near Taylor's Pass. Other paleomagnetic data are from compilations of *Roberts* [1992] and *Vickery and Lamb* [1995]. Circled numbers 1-4 denote rotation boundary segments. Bold letters indicate Torlesse terrane structural domains, as discussed in the text. For each domain, lower-hemisphere equal-area projections contain site bedding poles; great circles are mean bedding planes (N = number of sites/total number of measurements).

fabric. Moreover, restoration of paleomagnetic vectors to their unrotated positions should return the planar fabric of the underlying Torlesse basement to its pre-Cenozoic strike. Because early fold hinges define a near-vertical lineation, their uniformly steep attitude provides a test for the verticality of any fabric rotation axes. Thus, in principle, Torlesse fabrics can be used to map the distribution of vertical axis rotations across the plate boundary zone in New Zealand.

Crustal-Scale Rotation Boundaries in the Basement Rocks of NE South Island

Structural data and mapping results from NE South Island are compiled in Figure 4, with special emphasis on the Torlesse fabric, overlying Neogene strata, and their relationship to paleomagnetic rotations (arrows) in rocks of differing age (bold numbers). Basement rocks are divided into 26 domains (letters

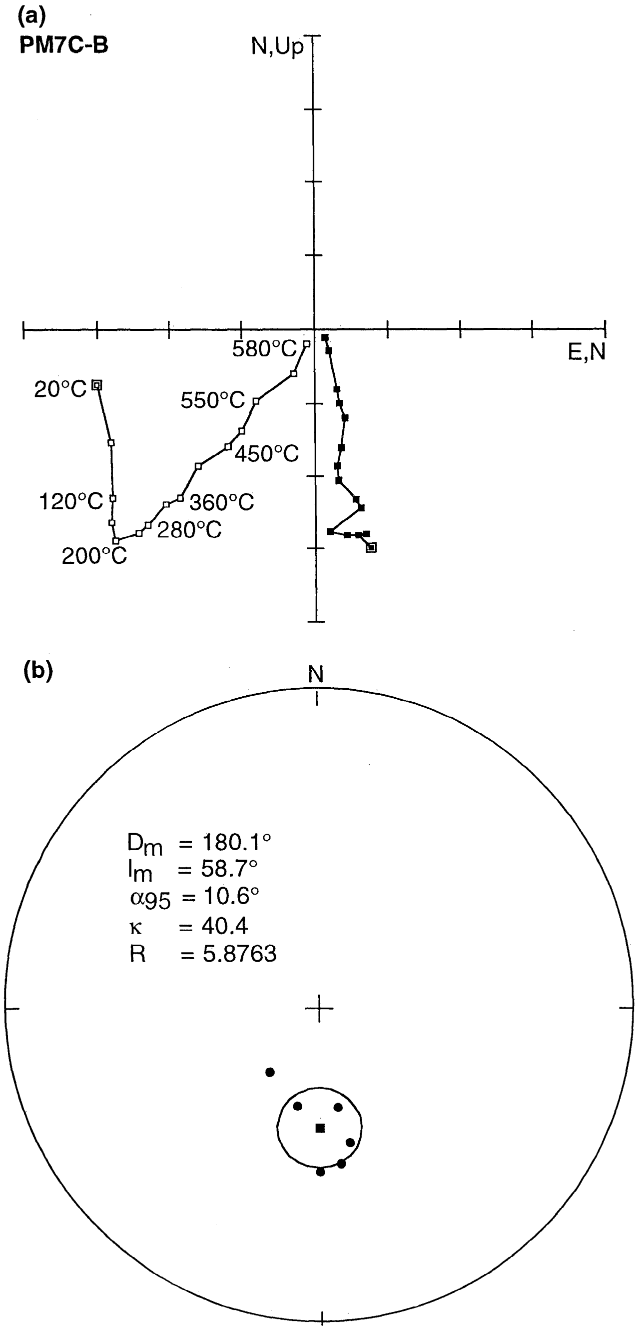


Figure 5. (a) Vector component plot of thermal demagnetization data for a stably magnetized sample with reverse polarity (PM7C-B) from Fuchsia Creek. Open (solid) symbols represent projections onto the vertical (horizontal) plane. (b) Equal-area (lower hemisphere) stereographic projection of tectonically-corrected site-mean paleomagnetic directions (solid circles), with locality-mean direction (solid square) and statistical parameters (see text for explanation).

A-Z) with a mean spacing of ~10-15 km. Except where distinct changes in strike occur, the boundaries between these domains are arbitrary. At each site or outcrop, bedding measurements (usually 4-6) were averaged on a sphere to obtain a mean bedding pole using the eigenvector technique for Bingham axial distributions [e.g., *Mardia*, 1972; *Woodcock*, 1977]. This "noise smoothing" is akin to averaging paleomagnetic secular variation. Most domains contain at least 15 sites, and some contain up to 68. Great circles, plotted on lower hemisphere, equal-area stereograms, depict mean bedding attitudes (Figure 4). Where structural data from other workers were used to define domain averages, site averaging could not be done, and the plotted great circles are averages of many equally-weighted measurements (e.g., domains U, V, W, X, and Z).

Variations in regional Torlesse strike patterns define three nearly co-linear, N or NW trending discontinuities that separate N or NNE striking bedding fabrics to the west from more E striking fabrics to the east (Figure 4, boundaries 1, 2, and 3). These boundaries are offset dextrally or sinistrally by as much as 5 km across major fault strands. As a whole, they define a single, crustal-scale structure that transects the Marlborough fault system. A fourth, more eastern, boundary (kink 4) emerges from the south of the Awatere basin between the Awatere and Clarence faults, where it separates ENE striking fabrics to the west from SE striking fabrics near the coast. This set of kink-like boundaries defines a broadly arcuate, double-hinged regional fold that deflects the dominantly N younging Torlesse fabric clockwise from its western strike of NNE (domains A-F, J, K, N, and O) or N (domains U, V, Y, and Z south of the Clarence fault) to an ENE strike closer to the coast (domains H, I, G, P, Q, R, W, and X, here referred to as the central limb), and ultimately to a SE strike (domain S, near Ward and Kekerengu, here called the eastern limb). The strongly rotated eastern limb occurs on the hanging wall of a SW directed reverse fault, the Flags Creek fault, which has been interpreted as the roof to an early Miocene thin-skinned thrust system [*Waters*, 1988; *Rait et al.*, 1991]. Although Torlesse terrane is only exposed in a narrow fault-bounded sliver to the east of the London Hill reverse fault (a post-Pliocene structure), the SE striking basement domain (domain S) is here inferred to extend offshore beneath Cook Strait (see discussion below).

Superimposed on the above described first-order structure, narrow (<3 km wide) domains of apparent dextral stratal rotation locally border the Awatere and Clarence faults (domains L, M, and T). These appear to be second-order features which reflect rotation of Torlesse bedding packets in brittle shear zones adjacent to those large finite slip dextral faults.

The vertical axis rotations that are inferred by statistical comparison of Torlesse fabric data on opposite sides of the mapped boundaries (Figure 4) are summarized in Table 1 and Figure 3. Across each numbered rotation boundary (Figures 3 and 4), structural data were grouped into two sets, one on each side of the hinge. Data for segment 1, between the Wairau and Awatere faults, are presented in Figure 6. Site means for domains D and F, to the west of the boundary, are combined in Figure 6a; site means for domains H and I, to the east, are combined in Figure 6b. The first eigenvector (E_1) describes the clustered aspect of a bedding pole distribution, giving its mean pole, whereas the third eigenvector (E_3) describes the planar or girdled aspect of the fabric, which indicates a mean axis of intra-domain folding [*Woodcock*, 1977]. The method of *Fisher et al.* [1987] for Bingham axial distributions was used to specify 95% confidence ellipses around these eigenvectors (Table 1 and Figure 6c). The mean bedding pole (E_1) for each domain has the smallest uncertainty region of the three eigenvectors (±4°-5° in trend, ±2° in plunge). E_1 trends on either side of boundary 1 indicate a 34°±11° clockwise shift in the mean pole of the central limb relative to that of the western limb. Corresponding changes in vector plunge are insignificant. Equivalent rotations (with larger uncertainties) also relate the other two sets of eigenvectors (Figure 6c), which can also explain the pattern of mesoscopic folding observed on either side of the boundary (Figures 6d and 6e). Eigenvalue magnitudes (Fig-

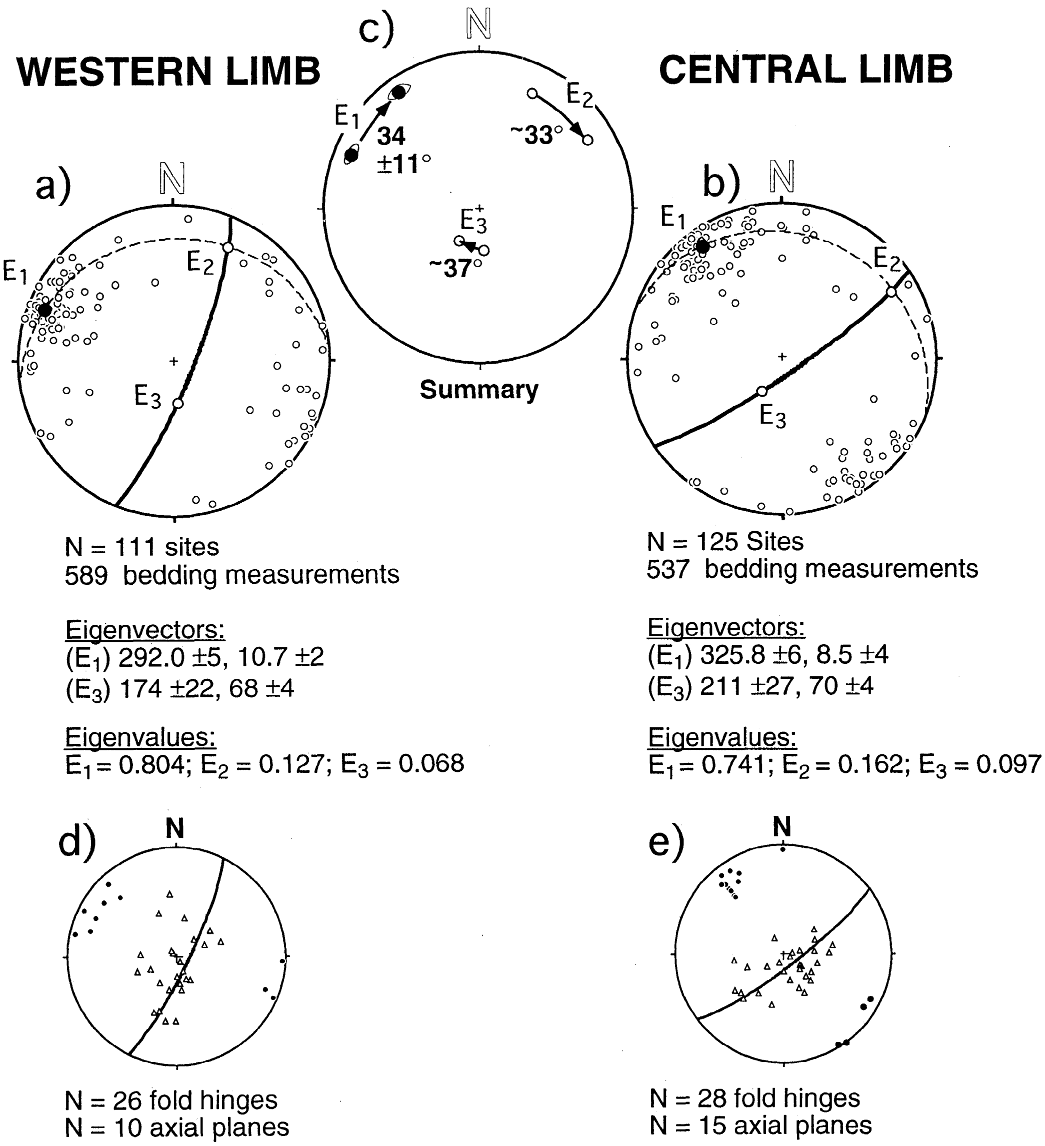


Figure 6. Lower-hemisphere equal-area stereograms: (a) site-averaged poles to bedding for domains D and F on the west side of boundary 1, and (b) site-averaged poles to bedding for domains H and I on the east side of boundary 1. Eigenvectors E_1 and E_3 [*Mardia*, 1972; *Woodcock*, 1977] are mean pole and girdle axes to the Bingham distributions, respectively. (c) Inferred vertical axis rotation of fabrics across boundary segment 1. Eigenvectors parallel to mean bedding poles on either side of the boundary (E_1) imply a vertical axis rotation of 34°±11° (95% confidence error ellipses are shown). For E_2 and E_3 eigenvectors, best fit rotations of 33° and 37° are inferred (error ellipses about these eigenvectors are larger than for E_1 and are not shown). (d) Geometric data for mesoscopic to kilometer-scale folds west of boundary segment 1. (e) Geometric data for mesoscopic to kilometer-scale folds east of boundary segment 1. Great circles are mean axial surfaces. See text for discussion of tectonic implications of these data.

ures 6a and 5b) indicate statistically indistinguishable shapes [*Lisle*, 1985] for bedding fabrics on both sides of the boundary. In short, differences in structural fabric across the boundary are completely described by a vertical axis rotation.

In Figure 7, paleomagnetically determined vertical axis rotations for sites in NE South Island (see Table 2) are plotted against apparent clockwise rotation of the Torlesse bedding fabric in the domain nearest each paleomagnetic site. The apparent rotations are measured relative to the mean N or NNE striking fabric of the western limb, immediately west of boundary segments 1, 2, or 3.

Four paleomagnetic sites lie on the western limb, one north of the Clarence fault (FC, this study) on a NNE striking Torlesse substrate (domain N), and three sites lie to the south of the Kekerengu fault (CS, WD1, and WD2) [*Roberts*, 1992; *Vickery and Lamb,* 1995] (Table 2), east of domain Y, which is N striking. All four of the inland sites are, within error, unrotated relative to the Pacific plate.

Paleomagnetic sites on the central limb lie in late Miocene to early Pliocene rocks and include two sites to the north of the Awatere fault (WV and WB) and five sites between the Awatere and Clarence faults (SV, BR, RB, UB, and BS) [*Roberts,* 1992]

Table 1. Summary of Changes in Torlesse Bedding Fabric Orientation Across Rotation Boundaries in NE South Island, New Zealand

Rotation Boundary	Domains: West Limb	Domains: East Limb	Trend, Plunge: E_1, West[a]	Trend, Plunge: E_3, West[a]	n, West[b] Sites/Total	Trend, Plunge: E_1, East[a]	Trend, Plunge: E_3, East[a]	n, East[b] Sites/Total	Fabric Rotation[c] degrees
Segment 1	E, F	H, I	292±5, 11±4	174±22, 68±4	111/589	326±6, 9±4	211±27, 70±4	125/537	34±11
Segment 2	N, O	P, R	286±10, 1±7	196±39, 15±6	27/117	162±9, 6±7	256±40, 30±8	44/183	56±19
Segment 3[d]	Z	W, X	092±9, 7±7	185±46, 22±8	39/39	315±4, 2±3	224±20, 5±3	339/339	43±13
Segment 3[d]	U	W, X	089±11, 17±9	192±49, 37±10	220/220	315±4, 2±3	224±20, 5±3	339/339	46±15
Segment 4	P, R	S	163±4, 5±4	256±40, 30±8	183/183	211±10, 22±9	302±57, 3±9	133/133	48±14

See Figure 3 for rotation boundaries.

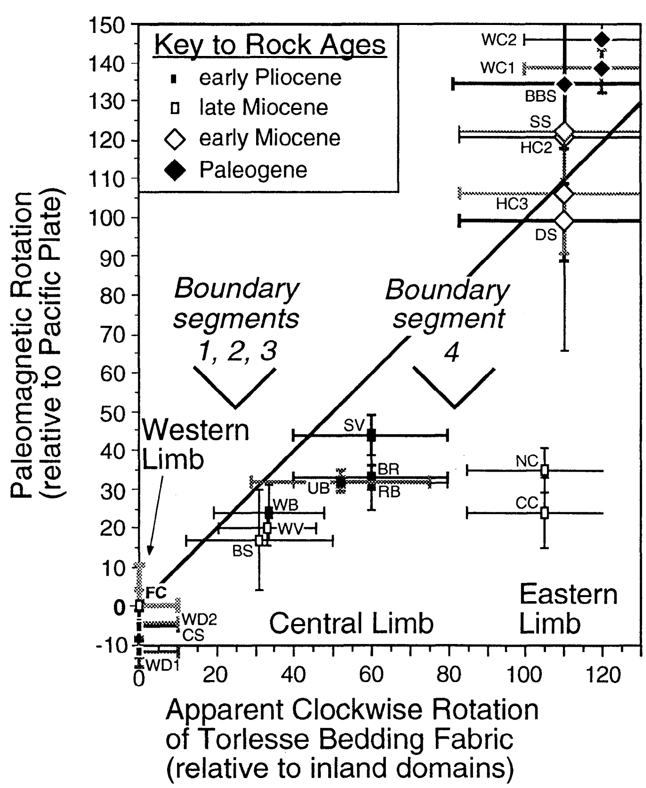
a. E_1 and E_3 are eigenvectors (maximum and minimum principal fabric axes) of the orientation matrix for the west and east limbs, respectively (Bingham axial distribution); E_1 is the first eigenvector (corresponds to mean bedding pole) and E_3 is the third eigenvector (mean apparent "fold axis"); 95% confidence ellipses (errors) about mean values were calculated using the program Stereonet 4.7 (by R.W. Almendinger) using the algorithm of *Fisher et al.* [1987].

b. Number of sites/total number of bedding measurements per bedding sample on the west and east limbs, respectively.

c. Amount of vertical axis rotation of east limb, relative to west limb, as inferred from differences in mean bedding strike across the respective rotation boundary.

d. Fabric rotation across segment 3 is calculated twice, using data from domain Z (or U) to establish the attitude of the western reference limb.

(Table 2). These sites overlie a NE to ENE striking Torlesse substrate (domains H, G, P, and R) and are clockwise rotated by 20°-40°. Removing the paleomagnetic declination anomalies by a vertical axis rotation restores the Torlesse fabric in the central and western limbs to statistical coincidence across boundary segments 1 and 2: a relationship that is illustrated by the data points on Figure 7, which plot near the reference line that has a positive slope of unity. The small discrepancy of 5°-10° for data points that lie below this line suggests that a small amount of clockwise basement rotation predates deposition of the early Pliocene strata from which many of the paleomagnetic data were obtained. Structural and paleomagnetic data across segments 1 and 2 therefore indicate that the mapped basement boundaries are accommodation zones for the observed late Neogene (post 4 Ma) vertical axis rotations.



Paleomagnetic sites on the eastern limb record a marked increase in clockwise rotation with stratigraphic age. Between the Awatere and Clarence faults, paleomagnetic sites in late Miocene rocks on the eastern limb (CC and NC) [*Walcott et al.,* 1981; *Roberts*, 1992] have undergone 20°-40° rotation (Table 2), equivalent to that of similar-aged rocks on the central limb. Thus the boundary between these two limbs in basement (segment 4) has been inactive since the late Neogene, thereby allowing these two regions to rotate together as a single block, as suggested by *Roberts* [1992]. This conclusion is supported by the late Miocene Flaxbourne fault [*Maxwell*, 1990], which is not deformed by boundary 4, but apparently crosscuts it. Early Miocene sites on the eastern limb have experienced large clockwise rotations of ~100°-120° (DS, SS, HC2 and HC3; Table 2), most of which occurred during early-mid Miocene time [*Vickery and Lamb,* 1995]. The magnitude of this finite paleomagnetic rotation closely matches the apparent clockwise rotation of the Torlesse bedding fabric above the Flags Creek fault (domain S), relative to that on the western limb (domains N and O). These sites, therefore, plot on or near the reference line in Figure 7. Subsequent to major clockwise rotation in the early-mid Miocene, fault slices beneath the Flags Creek fault were cut and offset ~18 km dextrally by Pliocene to present-day slip on the Kekerengu fault [*Vickery*, 1994] (Figure 4). Together, boundary segments 4 and 3 can account for accommodation of the >100° of post-early Miocene vertical axis rotation that affected the faulted and dismembered eastern limb.

Clockwise rotation occurred sequentially on the two sets of hinges: first, on boundary segment 4 in early to mid Miocene time (~18-8 Ma) [*Vickery and Lamb*, 1995], after which it

Figure 7. Rotation (relative to Pacific plate) of Cenozoic paleomagnetic localities in NE South Island (from *Roberts* [1992]; *Vickery and Lamb* [1995]) plotted against clockwise rotation of strike of bedding fabric in underlying Torlesse basement (relative to inland domains to west). The data are listed in Tables 1 and 2. Error bars are 95% confidence intervals about means. A line with slope of unity is shown for reference. Symbols indicate the age of paleomagnetically sampled strata (see key). See Table 2 for locality abbreviations.

Table 2. Vertical Axis Rotation Data From NE South Island, New Zealand

Locality	Abbreviations[a]	Age, Ma	Paleomagnetic Rotation, degrees	Mean Strike		Fabric Rotation, degrees[b]	Reference[c]
				Basement Domain[b]	Inland Reference Domains[b]		
Fuchsia Creek	FC	5.5±0.5	0±11	N	N	0±10	1
Camp Stream	CS	3.3±0.3	-5±4	Y	Y	0±10	2
Washdyke Stream	WD1	4±1	-11±5	Y	Y	0±10	3
Washdyke Stream	WD2	4±1	-4±8	Y	Y	0±10	3
Boundary Stream	BS	8±1	17±13	Q (228±9)	N, O (196±10)	32±19	2
Waihopai Valley	WV	8±1	20±4	H (055±8)	D (022±5)	33±13	2
White Bluffs	WB	3.9±0.8	24±7	G (056±10)	D	34±15	2
Upton Brook	UB	4.8±0.2	32±3	P (249±13)	N, O	53±29	2
Richmond Brook	RB	4.2±0.6	32±7	R (256±7)	N, O	60±17	2
Blind River	BR	4.8±0.2	33±3	R	N, O	60±17	2
Sea View	SV	3.9±0.8	44±5	R	N, O	60±17	2
Cape Campbell	CC	8±1	24±9	S (301±10)	N, O	105±20	4
Needle's Creek	NC	5.4±0.6	35±6	S	N, O	105±20	2
Deadman Stream	DS	18±1	99±10	S	Y (191±18)	110±28	5
Heaver's Creek	HC2	17±1	121±55	S	Y	110±28	3
Heaver's Creek	HC3	17±1	106±15	S	Y	110±28	3
Silver Springs	SS	20±4	122±12	S	Y	110±28	3
Boo Boo Stream	BBS	30±5	135±17	S	Y	110±28	3
Woodside Creek	WC1	59±5	138±6	S	Z (182±9)	120±21	3
Woodside Creek	WC2	59±5	146±11	S	Z	120±21	3

a. Abbreviations are as in Figures 3 and 6.

b. See Torlesse bedding fabric data (this study) from Table 1 and Figures 4 and 7. Rotations (positive clockwise) are given with 95% confidence intervals.

c. Paleomagnetic data are compiled from: 1. This study; 2. *Roberts* [1992]; 3. *Vickery and Lamb* [1995]; 4. *Walcott et al.* [1981]; 5. *Mumme and Walcott* [1985].

became inactive, and, second, on boundary segments 1-3 in the post-late Miocene (<4 Ma) [*Roberts*, 1992]. The locus or hinge of vertical axis rotation of coastal blocks in the Marlborough fault system has thus migrated SW with time.

Three coastal paleomagnetic sites in rocks of Paleocene-Oligocene age (WC1, WC2, and BBS) [*Vickery and Lamb,* 1995] are rotated ~120°-140° (Table 2). We infer that the extra ~20°-40° of rotation experienced by these rocks relative to the Pacific plate (1) is pre-Miocene in age and (2) cannot be attributed to rotation on the nearby basement discontinuities (these data plot well above the line in Figure 7).

Crustal Rotations in Relation to Neogene-Quaternary Structures

The crustal-scale boundaries that we have identified in the Torlesse basement must postdate the Early Cretaceous depositional age of the Pahau subterrane. Correlation of mean strike of Torlesse bedding fabric with paleomagnetic declination anomalies in the overlying Neogene cover (Figure 7) implies that the basement hinges are plate boundary-related structures of early Miocene or younger age. Further evidence for the Neogene and younger age of the rotations is presented below.

Deformation of the Awatere Basin

Late Miocene strata in the Awatere basin overlie the Torlesse terrane along an angular unconformity that dips variably NW to NE at 15°-35°, and locally at up to 50° (Figure 4). Most tilting and folding in the basin postdates the early late Pliocene (<3 Ma) [*Roberts and Wilson,* 1992], and some gently NNE plunging folds, such as the Ward and Cape Campbell synclines are active [*Uruski*, 1992; *Browne*, 1992a; *Little*, 1995; *Townsend*, 1996] (Figure 4). We have returned the mean of the Torlesse fabric to its inferred pre-Neogene strike (ball-and-bar symbols, Figure 4) by rotating the unconformity back to horizontal about its local strike. This restoration generally steepens the Torlesse fabric slightly, without significantly changing its strike. The back-tilted strike azimuths define the basement hinges as well as the raw data (Figure 4).

The strike of bedding in the Awatere basin deflects across boundary segments 2 and 4, which indicates a Neogene age for those structures (Figure 4). Segment 2 is most conspicuous in relation to the Haldon and Flaxbourne faults in the late Miocene Medway fault system. West of the hinge, these structures strike NE and dip steeply NW; east of it, they strike ESE or E and dip steeply N [*Maxwell,* 1990]. The ~50°-55° angle between the two strikes duplicates the 56°±18° vertical axis rotation inferred from Torlesse fabrics across segment 2 (Figure 3 and Table 1). The late Miocene age of the dextral-reverse separation faults [e.g., *Melhuish,* 1988] is in accord with the <4 Ma age of vertical axis rotations east of boundary segment 3 [*Roberts,* 1992]. East of segment 4, marked deflection of bedding strikes from NW to NNE chiefly reflects rotation about the subhorizontal hinge of the Ward syncline (Figure 4).

Clockwise Rotation of the Coastal Ends of the Marlborough Faults

The coastal ends of the major faults in the Marlborough fault system have rotated clockwise relative to their inland segments. These rotations are hinged at or near the basement structures described above. Clockwise bending of the Alpine-Wairau fault across Cook Strait is expressed by mismatch between this >1500 km, NE striking transform fault and North Island faults which lie <30 km away [*Walcott*, 1978b; *Carter et al.*, 1988]; ~140 km dextral offset of the Esk Head subterrane at the southern tip of the North Island relative to the same unit on the SE side of the Alpine fault [*Mazengarb et al.,* 1993; *Begg and Mazengarb*, 1996]; and by the recurved shape of the

Wairau basin, which contains 2.5-3 km of late Miocene-Holocene strata [*Carter et al.*, 1988; *Uruski*, 1992]. The Alpine-Wairau fault curves from a strike of 070° to 090° as it extends offshore into Cook Strait, then bends SE to pass south of the North Island, truncating major NNE striking faults and related subbasins at their southern ends [*Lewis et al.*, 1994] (Figure 3). The NE margin of the Wairau basin parallels the steep continental slope between the North Island and Cook Strait, across which the Aorangi Mountains gravity high (>200 mGal) is juxtaposed against the Cook Strait gravity low (<-90 mGal) [*Ivory*, 1986]. This profound anomaly reflects dextral offset of the continental margin across the clockwise-rotated, ancestral Alpine-Wairau fault [*Walcott*, 1978b; *Dunkin*, 1995]. Clockwise rotation of the offshore Alpine-Wairau fault is here attributed to rotation about the NE continuation of boundary 4 into Cook Strait.

Relative to the currently active coastal strand of the Awatere fault, older, more clockwise-striking faults to the south define a fan-like array which indicates progressive rotation of the eastern end of the Awatere fault about hinge segment 2 (Figure 4). The active strand strikes NE, it has <4 km of post-Pliocene dextral-slip, and it is probably <2 m.y. in age [*Little et al.*, in press]. Another active scarp, the Vernon fault, occurs a few kilometers to the north. Inactive strands to the south are partially buried by >1.3 km of early-late Pliocene marine strata [*Roberts and Wilson*, 1992] and are mantled by late Quaternary alluvial terraces [*Eden*, 1989]. These include (1) the ancestral Awatere fault and (2) the Hog Swamp fault. The ancestral Awatere fault has >30 km of post-late Miocene dextral slip and has been inactive since at least ~350 ka [*Little et al.*, in press]. It diverges eastward from the main fault near rotation boundaries 1 and 2 and juxtaposes contrasting late Miocene-early Pliocene facies [*Little et al.*, in press]. Striking ~20° clockwise from the active strand, the Hog Swamp fault has no surface trace and only minor recognizable Pliocene-Quaternary geological offset [*Adams and Lensen*, 1970; *Townsend*, 1996]. Gravity data indicate ~160 m of vertical offset of the Torlesse unconformity surface across the Hog Swamp fault, implying the possibility of a large pre-Pliocene strike-slip on this buried structure [*Hunt*, 1969]. We interpret this fanned system of faults as evidence of (1) clockwise rotation of structures about hinge segment 2, followed by initiation of new coastal faults, and (2) termination of the Awatere fault near the coast. Misalignment of rotated strands may have caused replacement by in-plane (NE striking) fault splays that are mechanically favored for earthquake rupture propagation [e.g., *Scholz*, 1990].

The eastern ends of the Clarence and Kekerengu faults are deflected by ~20°-25° across boundary segment 3 [*Lensen*, 1963; *Prebble*, 1976; *Kieckhefer*, 1979; *Vickery*, 1994] (Figure 4). These bends provide clear evidence of late Quaternary rotation across the western boundary system. The coastal end of the Clarence fault is deformed across segment 4. Its hinge zone is defined by (1) an abrupt ~48°±14° change in strike of bedding fabric across a ~400-m-wide zone of microbreccia and cataclasite [*Browne*, 1992b]; (2) a distinct change in azimuth of sandstone strike ridges; and (3) the ~50° junction between the Clarence and Flags Creek faults. The Flags Creek fault dips steeply NE but can be traced no further inland than the Clarence fault, which dips NW. No Cenozoic or late Quaternary trace is evident for the Clarence fault seaward of this junction [*Browne*, 1992b]. Structural fabrics along the NW striking Flags Creek fault indicate chiefly dextral strike slip [*Vickery*, 1994, pp. 48-51]. These relationships suggest that the Flags Creek fault is a deformed coastal part of the Clarence fault that was rotated ~50° clockwise in the Miocene across hinge segment 4.

Short-Term Velocity Fields Inferred From Geodetic Strain and Kinematic Modeling

Walcott [1984b, 1989] and *Lamb* [1988] smoothed the retriangulation survey shear strain rate data of *Bibby* [1976, 1981] to obtain a model for the velocity field across the northern South Island during the past century. Relative to a fixed Pacific plate, these data indicate an E to SE swing in velocity azimuth near the east coast. *Lamb* [1988] interpreted this pattern to represent clockwise rotation of the northeastern Marlborough fault system relative to the Australian and Pacific plates. Based on this velocity pattern, he approximated poles of rotation for crustal blocks that are bounded by the Awatere and Wairau faults, relative to both plates ("A" and "P," Figure 3). Estimated rates of angular rotation for these poles are of the order of 6°-9°±5°/m.y. [*Lamb*, 1988]. Because rocks within the Marlborough fault system belong to neither the Pacific nor the Australian plate, any local poles of rotation between adjoining crustal blocks in the Marlborough fault system will lie between these two extremes. In summary, the geodetically measured short-term velocity field (1) is consistent with the above-described segment boundaries being the locus about which clockwise rotation of the eastern Marlborough fault system is continuing today, and (2) predicts the existence of active rotation-accommodating structures in that general region.

Using a finite element method, *Holt and Haines* [1995] evaluated a longer-term (10^3-10^4 years) Pacific-Australian plate velocity field in the Marlborough fault system, based on inversion of Quaternary fault-slip, rock-uplift, and erosion rate data. By fitting the strain rate distribution to polynomial spline functions, and keeping plate interiors rigid, they obtained a velocity field that arises from slip on major faults that is broadly consistent with the Nuvel-1a model of plate motion [*DeMets et al.*, 1990]. Their finite velocity field, projected 1 m.y. into the future, is reproduced here in Figure 8. Note the increase in clockwise rotation along the strike of the Marlborough fault system near the coast. The grid is deformed into a crustal-scale kink similar to the structures mapped to much higher resolution in Figure 4. The modeled deformation gradient is a consequence of the boundary condition [*Holt and Haines*, 1995, Appendix B] that slip rates on each of the major faults in the Marlborough fault system decrease eastward before terminating offshore.

Structural Boundaries of a Rotating Crustal Block

The structural data presented here precisely define the boundaries of the actively rotating Northern Marlborough Domain, thereby providing constraints on structural mechanisms that accommodate vertical axis rotations in the brittle crust.

Southwestern Boundary Zone

The western system of hinges is ductile at the kilometer scale. For boundary segment 1, the 34°±11° change in strike occurs across a zone that is ~100-500 m in width. At the outcrop scale, pervasive (<1 m spacing) faulting and jointing is characteristic of, but is not restricted to, this zone. The northern end of segment 1 bifurcates into a triangular system of NNE striking normal faults (Waihopai extensional domain, Figure 4) that cut and offset Pliocene-Quaternary gravels. The ~70° E

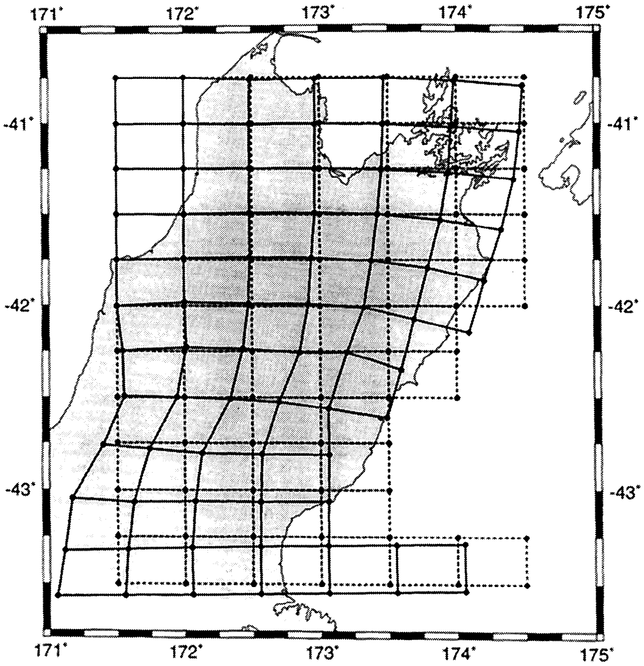


Figure 8. Map of finite deformation of a grid in NE South Island, New Zealand, calculated 1 m.y. into the future by fitting continuous polynomial spline functions to the three components of the strain rates that have been inferred from geologic data and that have been integrated with respect to time (from *Holt and Haines* [1995]). Note rotation of the grid in the coastal region where slip on the Marlborough faults dies out.

dipping dip-slip Waihopai fault offsets the gravel-Torlesse contact by 350-400 m and the remnants of a gently N dipping alluvial terrace above these gravels by 200±50 m, but it does not cut Holocene terrace gravels ("Wairau surface"). To the east, other faults in the Waihopai extensional domain strike slightly clockwise of the Waihopai fault (Figure 4). ESE crustal extension in the Waihopai domain deviates from the ESE direction of crustal shortening that is observed geologically and geodetically throughout the Marlborough fault system [e.g., *Bibby*, 1981]. We interpret the domain to be a pull-apart basin which reflects tangential extension of a crustal block that is flexed across rotation boundary 1 (Figures 9a and 9b). A conspicuous 25°-40° sigmoidal deflection of ridges within ~5 km of the inland Wairau fault records a second type of flexure-accommodating internal deformation: distributed dextral shear. Such sigmoids in the Raglan and St Arnaud Ranges imply finite shear strains of 2-3 (Figure 9a).

Segments 2 and 3 have a distinct geomorphic expression that is defined by a deflection of erosion resistant sandstone strike ridges. Structural data define a hinge zone that is 0.5-2 km in width. A brittle overprint has shattered many outcrops within this zone, most obviously the tens-of-meters-thick massive sandstone units that support the strike ridges.

Northern Boundary Zone

The active trace of the Alpine-Wairau fault is not deflected across segment 1. The Alpine-Wairau fault forms a nearly continuous surface trace for >1500 km in the South Island but it becomes poorly defined east of hinge segment 1. About 5 km east of segment 1, the northern scarp of the Wairau fault terminates; ~5 km farther east, its southern strand disappears beneath alluvium [*Lensen*, 1976a, b]. Nearer the coast, a subtle fault trace reemerges for 10 km, but it vanishes in beach ridges within 800 m of the shoreline [*Grapes and Wellman*, 1987]. We infer that this change in scarp expression may reflect a decrease in late Quaternary dextral-slip rate, which is measured at 3.5-6 mm/yr to the west of segment 1 [*Lensen*, 1976a, b; *Grapes and Wellman*, 1987; *Eden*, 1989]. East of segment 1, in the lower Wairau Valley, a coastward-widening, wedge-shaped zone of oblique crustal extension can be inferred from (1) an abrupt increase in the width and thickness of valley fill at the Waihopai River, (2) tectonic subsidence of the lower Wairau plain (~2.8 mm/yr since ~18 ka) [*Ota et al.*, 1995], and (3) gravity data [*Lock*, 1995] which indicate no vertical offset of Pliocene-Quaternary gravels across the Wairau fault west of segment 1 (Waihopai fault), whereas the gravels thicken by ~200 m against the SE dipping Wairau fault to the east of seg-

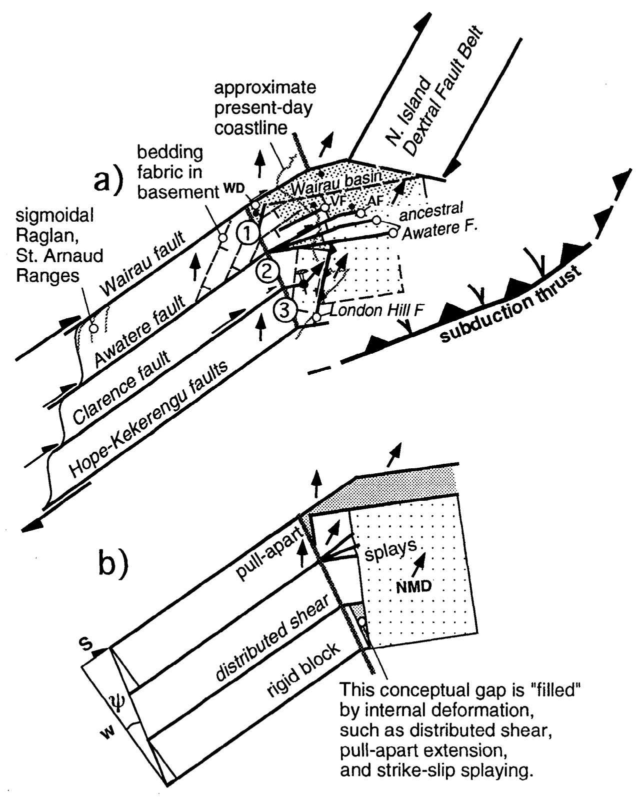


Figure 9. (a) Schematic diagram of structural boundaries of the rotating Northern Marlborough Domain (NMD, light stipple pattern). See Figures 3 and 4 for more detail on offshore/onshore fault patterns. Densely stippled regions are undergoing oblique extension. Arrows indicate post-Pliocene vertical axis rotations. WD is Waihopai extensional domain; VF is Vernon fault; AF is active strand of the Awatere fault. Note ~10° extra rotation of the subblock in the Northern Marlborough Domain east of the Clarence fault termination (see *Roberts* [1995]). (b) Kinematic framework for understanding bounding structures of the Northern Marlborough Domain and internal deformation of fault blocks. Variables are: s, dextral-slip; w, width of fault zone, ψ, angular shear. The condition of the flexed rigid block (bottom layer) requires a gap to open against the eastern rotated block. This gap can be closed by distributing dextral shear uniformly across the block (as in central layer) or by horsetail splaying of strike-slip faults and localized extension (as in top layer).

ment 1 (Figure 9a). Oblique extension in the Wairau basin is suggested by >300 m of post-Pliocene throw on the Vernon fault [*Hunt*, 1969] and by normal offset of Miocene-Pleistocene reflectors by other steeply-dipping offshore faults [*Carter et al.*, 1988; *Uruski*, 1992; *Lewis et al.*, 1994] (Figures 3 and 4). Figure 9b represents a simple interpretation of these relationships. Because faults in the Wairau basin are attached to the eastern limb of segment 1, and the Wairau fault is not, they have rotated clockwise away from segment 1 to define a zone of oblique divergence and subsidence. The Wairau basin marks a velocity discontinuity at the northern edge of the Northern Marlborough Domain, which is rotating clockwise relative to adjacent rocks on the Australian plate.

Southeastern Boundary Zone

Between the Awatere and London Hill faults, late Miocene-Pliocene rocks have rotated 30°-45° clockwise; whereas, NE of these structures, they have rotated only ~20° (Figure 3) [*Roberts*, 1995]. This observation is supported by the Torlesse bedding fabric data, which indicate 56°±19° of relative rotation east of boundary 2, but only 34°±11° of rotation east of boundary 1 (Figure 3 and Table 1). Thus the actively rotating region on the eastern limb of the near-coastal hinge system is divided into subblocks by the Awatere fault. *Roberts* [1995] pointed out that the more rapidly rotating southern block overlaps spatially with the termination of the Clarence fault and attributed its extra rotation to dextral shear that has been distributed northward from that termination (Figure 9a). South of the Awatere fault, fault slip data from coastal Pliocene rocks indicate oblique-normal deformation with an E-W direction of principal horizontal shortening [*Little*, 1995, 1996]. Farther to the SE, toward Cape Campbell, strike-slip fault sets indicate a principal horizontal shortening direction that trends ESE, subparallel to that measured regionally in geodetic surveys. Farther south, the faulting-related shortening direction swings to SE near the London Hill fault, which has 1.5-2.25 km of post-Pliocene reverse throw [*Townsend*, 1996]. These data define a rapidly changing kinematic pattern that is regionally anomalous but which can be simply understood in the context of a rotating block that is pinned to the end of the Clarence fault [*Roberts*, 1995] (Figure 9a).

Discussion

Relationship of Rotations to Plate Tectonics

Why has a coastal part of the Marlborough fault system rotated clockwise since the Miocene? The eastern boundary of the rotating Northern Marlborough Domain is the Hikurangi margin [*Lamb*, 1988], beneath which the Pacific plate is subducted to depths >250 km to the NE of the heavy dashed line in Figure 3 and to depths >100 km to the SW of it [*Anderson et al.*, 1993] (Figure 10). On the upper plate of this margin, the

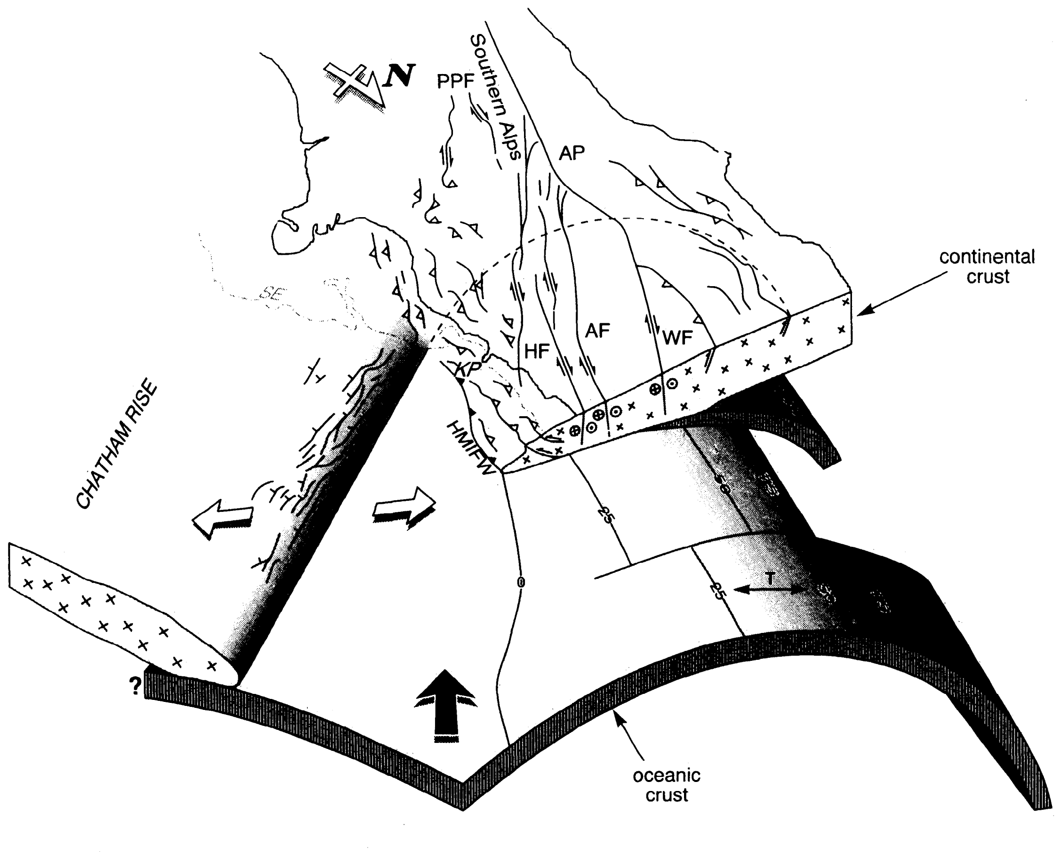


Figure 10. Oblique view parallel to the direction of plate motion (large solid arrow) of the transition zone that links subduction at the Hikurangi margin imbricate fault wedge (HMIFW) to strike-slip on the Marlborough faults to oblique slip on the Alpine fault (AP). Oblique collision of the continental Chatham Rise (extending parallel to open arrows) and the position of the subducted slab of the Pacific plate beneath the Marlborough fault system (PPF, Porter's Pass fault; HF, Hope fault; AF, Awatere fault, WF, Wairau fault) are illustrated. KP is Kaikoura Peninsula. Contour lines on the down-going slab are in kilometers. Reproduced from *Barnes* [1994].

strike-slip faulted forearc and accretionary wedge are being translated eastward over rocks that are attached to the Pacific plate. The present slab geometry requires ocean floor of the Pacific plate to have been subducted beneath NE South Island since 10-25 m.y. [e.g., *Lamb and Bibby*, 1989; *Beanland*, 1995]. South of Cook Strait, interplate coupling increases where the Pacific plate becomes continental and cannot be fully subducted [*Eberhart-Phillips and Reyners*, 1997]. The subduction zone is pinned at its southern end to the buoyant Chatham Rise on the Pacific plate (here assumed to be fixed), but is attached at its northern end to the Hikurangi forearc (part of the Australian plate, which is moving east). Thus the margin has a velocity gradient along its length and its azimuth must rotate clockwise [*Walcott*, 1989].

Neogene plate reconstructions suggest that the Hikurangi forearc has rotated clockwise from a WNW trend in the early Miocene to its present NE azimuth, and paleomagnetic data confirm that vertical axis rotations have played an important

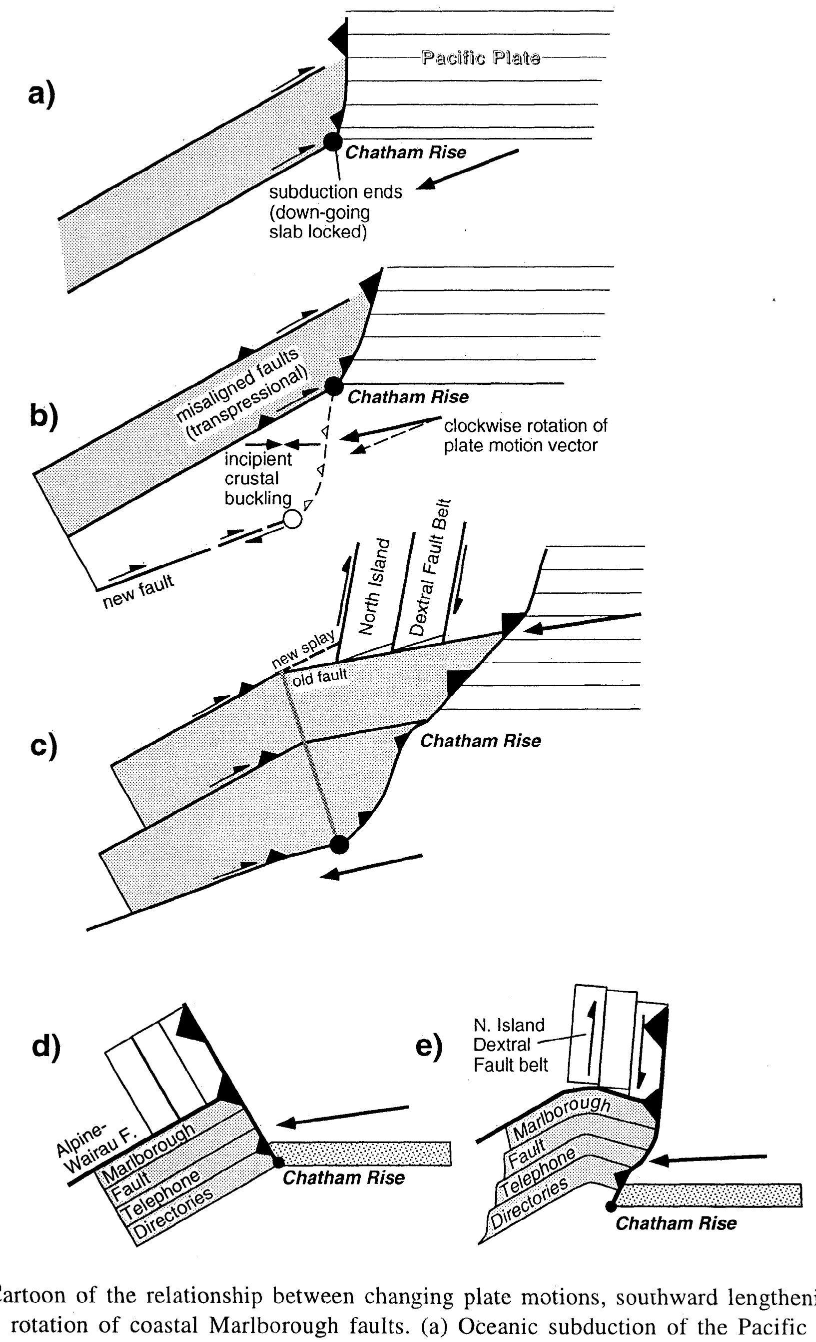


Figure 11. Cartoon of the relationship between changing plate motions, southward lengthening of the plate boundary, and rotation of coastal Marlborough faults. (a) Oceanic subduction of the Pacific plate links into continental strike-slip faulting across the continent-ocean boundary. The southern end of the subduction margin is pinned to the buoyant, continental part of the Pacific plate (Chatham Rise). (b) Clockwise change in plate motions causes upper plate transpression and incipient buckling of the Pacific plate. Chatham Rise becomes an oblique indentor and a new strike-slip fault propagates into undeformed continental Pacific plate. (c) The buckled coastal block is captured by the strike-slip fault system as the subduction margin jumps southward. Dextral shear (ψ) on the inland strike-slip fault system is transformed into coastal rotation (δ). (d) and (e) A telephone-book model further illustrates the relationship of the original plate boundary configuration (d) to oblique collision of Chatham Rise, southward-translation of the Hikurangi margin, and rotation of the Marlborough faults and Northern Marlborough Domain (e).

role in this process along the east coast of the North Island [*Wright and Walcott,* 1986; *Lamb*, 1988; *Walcott*, 1989; *Beanland*, 1995]. The Northern Marlborough Domain, to the south, has also rotated clockwise during the Neogene; some have argued as a single block [*Lamb*, 1988; *Roberts*, 1992], as a series of elongate transpressional fault blocks [*Lamb and Bibby*, 1989], or as a stack of thrust sheets that are pinned to the Chatham Rise to the south [*Vickery and Lamb*, 1995]. Most of these models postulate that the Northern Marlborough Domain is hinged near the dashed line in Figure 3. This hypothesis is not supported by our new paleomagnetic and structural data. Rather, these data indicate that most of Marlborough has not rotated since the Miocene. Only a small, near-coastal part of the margin has rotated clockwise relative to the Pacific plate. The rotation hinge is located well north of Kaikoura, and, rather than being fixed in position, it has shifted to the SW with time.

In addition to the southward increase in interplate coupling, first-order boundary conditions that contribute to vertical axis rotations in NE South Island are threefold. First, the pole of Pacific-Australian rotation has migrated southward throughout the Cenozoic, causing the azimuth of relative plate motion to shift from NE-SW in the early Miocene to E-W today [*Walcott*, 1984a; *Sutherland*, 1995]. Any faults that were aligned parallel to the plate motion vector could function as kinematically stable strike-slip faults for a limited time before the changing Euler pole caused them to become oblique to the plate motion vector, thereby requiring transpressional slip. *Anderson et al.* [1993] have argued that increasing convergence has been partially accommodated by slip on reverse faults in the Buller region (Figure 3). Second, dextral-slip faults of the North Island dextral fault belt have displaced the Hikurangi margin SSW to indent into the more ENE striking Marlborough faults of the South Island. Cook Strait marks the original intersection of the Alpine-Wairau fault with the Hikurangi margin, which today coincides with a zone of fault termination at the northern margin of the Northern Marlborough Domain. Third, the Hikurangi subduction margin has propagated southward into the Pacific plate during the Neogene, which has progressively widened the Marlborough fault system in the wake of this lengthened boundary. Thus the Wairau fault is now severely rotated and deformed [*Walcott*, 1978b], whereas the Porter's Pass fault at the southern edge of the Marlborough fault system is incipiently developing [*Cowan*, 1992]. The coastal Wairau, Awatere, and Clarence faults strike obliquely to the plate motion vector, whereas the Hope fault, to the south, strikes within ~10° of the plate-motion vector and is the current locus of plate motion with a slip rate of 8-43 mm/yr [*Cowan*, 1990; *Kneupfer*, 1992]. Other evidence for southward propagation of the Hikurangi subduction margin includes (1) continuation of seismically active slab to the SW of Kaikoura [*Anderson et al.*, 1993], (2) lack of Cenozoic deformation south of the Hope fault until the early Pleistocene [*Nicol*, 1992; *Nicol et al.*, 1994; *Barnes*, 1996], (3) southward migration of deposition in the Wanganui basin (Figure 3) and of the locus of North Island low-K andesitic volcanism since 5 Ma [*Stern and Davey*, 1989], and (4) the SW shift between the two rotation hinges in NE Marlborough (this study).

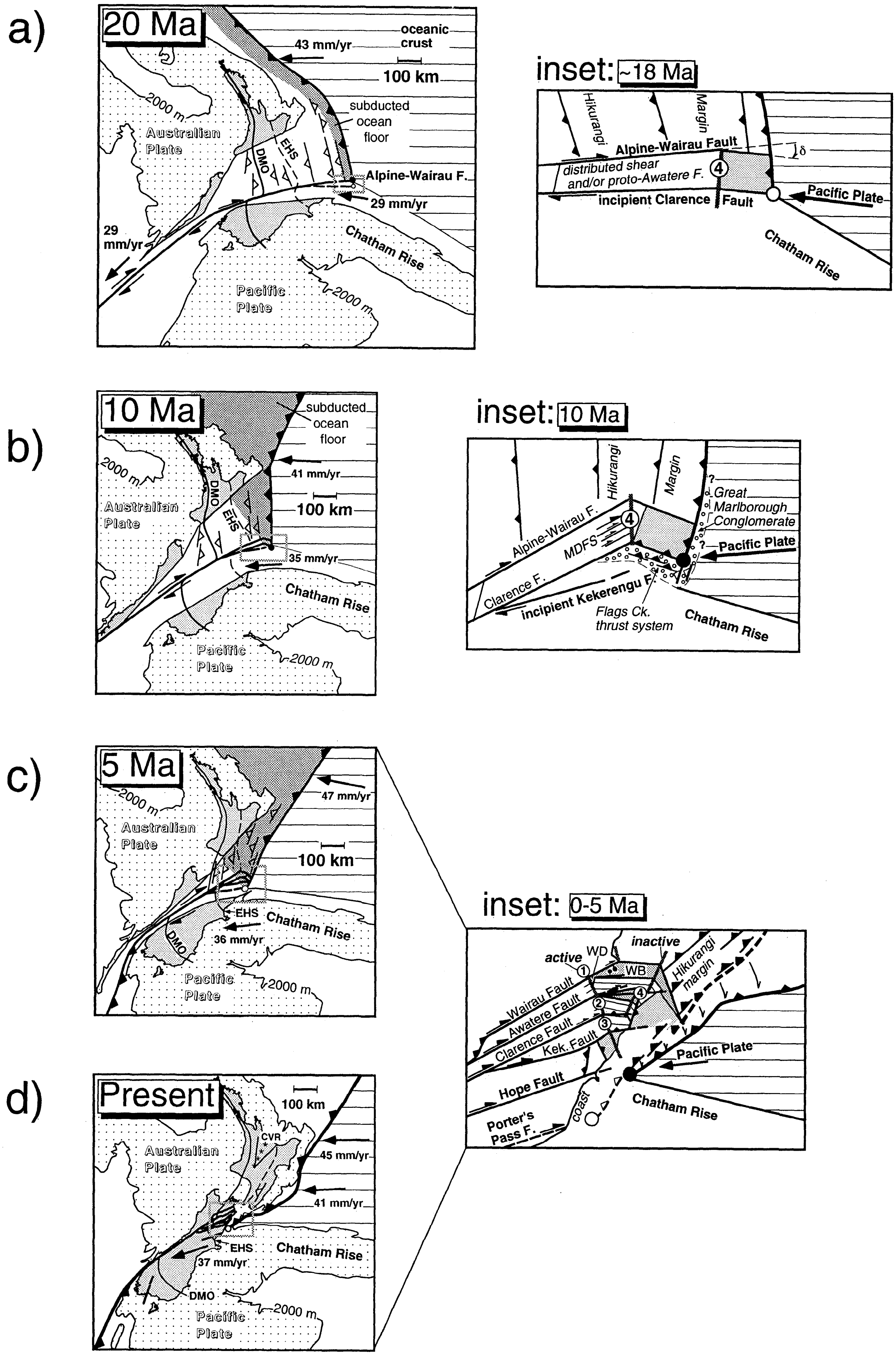
The locked end of the subduction interface is a rotation "pivot." The Marlborough fault blocks are driven clockwise over other rocks of the Pacific plate. Progressive increase in convergence at the Chatham Rise causes extant strike-slip faults to become mis-oriented and new well-oriented structures to form in undeformed Pacific plate to the SW. As the plate motion vector changes, the Chatham Rise collides obliquely into the margin (Figures 11a, b). Stresses at this indentor cause new, ideally-oriented strike-slip faults to initiate in undeformed continental rocks farther to the south (the modern example is the Porter's Pass fault). As new faults propagated eastward, dextral shear stress increased at the ends of a near-coastal domain of still-unbroken rocks, leading to incipient crustal buckling and clockwise rotation of continental blocks that are supported at depth by subducted oceanic crust of the Pacific plate (Figures 11b, c). Dextral slip on inland strike-slip faults is transformed seaward across a zone of fault termination into rigid body rotation and eastward thrusting of the near-coastal domain (Figures 11d, e). Further north, slip on the North Island dextral fault belt [*Beanland*, 1995] has caused the Hikurangi margin to impinge >10 km southward into the Northern Marlborough Domain since the late Pliocene, in part controlling the location of its western hinge.

Relationships between vertical axis rotation, plate motions, and the SW limit of the subducted slab are shown in Figures 12a to 12d for: 20-18 Ma, 10 Ma, 5 Ma, and the present-day, respectively. The mechanism of South Island vertical axis rotations resembles that of the Transverse Ranges, California. Both are transpressive margins that are underlain by subducted oceanic crust at depths of 10-20 km [*Yeats and Berryman*, 1987; *Anderson et al.*, 1993; *Nicholson et al.*, 1994]. In both settings, oblique plate motions have been transferred across a strongly coupled slab interface into an overriding plate that contains misoriented faults that were inherited from a time of different plate motions [*Luyendyk*, 1991]. Rotation in both cases swept inland with time, was coeval with lengthening of a plate boundary, and involved capture of near-coastal crust that was pinned at one end to a continental plate [*Luyendyk and Hornafius*, 1987; *Luyendyk*, 1991; *Nicholson et al.*, 1994].

Structural Mechanism of Vertical Axis Rotations

Transfer of motion from fault slip into block rotation is strongly implied by the seaward dying of slip on faults in the Marlborough fault system [*Little et al.,* in press], and by geodetic data. Rotation of rigid blocks within shear zones depends on the motion of the boundaries, on the attitude of blocks within the zone, and also on the mechanism by which rotation is imparted to the blocks. Because the rotation mechanism determines slip between adjacent fault blocks and the degree of continuity across the hinge, structural observations can constrain rotation mechanisms. Figure 1 is a summary of kinematic models that have been proposed for faulted regions that have undergone vertical axis rotations. The models specify relative fault block rotations only [*Jackson and McKenzie,* 1989].

For each of these models, different relationships between rates of rigid body rotation and shear strain are predicted. Clearly, these models are simplifications and are not mutually exclusive. In an area-conservative model of unpinned strike-slip fault blocks [*Freund*, 1974; *Ron et al.*, 1984; *Nur et al.*, 1986], the hinge boundary is stretched and the rotating domain must deform, for example, by oblique-normal faulting (Figure 1a). In the trellis model, fault blocks are pinned to a rotation boundary of fixed length [*McKenzie and Jackson*, 1983; *Jackson and Molnar*, 1990] (Figure 1b). Oblique-slip occurs between fault blocks but the rotating domain is rigid. In the double-slat model (Figure 1c), the clockwise-rotated domain is sinistrally faulted. In combination with the model


a)
20 Ma
oceanic crust
43 mm/yr
100 km
subducted ocean floor
2000 m
Australian Plate
DMO
EHS
Alpine-Wairau F.
29 mm/yr
29 mm/yr
Chatham Rise
Pacific Plate
2000 m
inset: ~18 Ma
Hikurangi
Margin
Alpine-Wairau Fault
δ
distributed shear and/or proto-Awatere F.
4
incipient Clarence Fault
Pacific Plate
Chatham Rise
b)
10 Ma
subducted ocean floor
2000 m
DMO
EHS
Australian Plate
41 mm/yr
100 km
35 mm/yr
Chatham Rise
Pacific Plate
2000 m
inset: 10 Ma
Hikurangi
Margin
Great Marlborough Conglomerate
Alpine-Wairau F.
4
MDFS
Pacific Plate
Clarence F.
incipient Kekerengu F.
Flags Ck. thrust system
Chatham Rise
c)
5 Ma
2000 m
Australian Plate
47 mm/yr
100 km
EHS
Chatham Rise
DMO
36 mm/yr
Pacific Plate
2000 m
inset: 0-5 Ma
inactive
active
WD
WB
Hikurangi margin
Wairau Fault
Awatere Fault
Clarence Fault
Kek. Fault
Pacific Plate
Hope Fault
Chatham Rise
Porter's Pass F.
coast
d)
Present
100 km
Australian Plate
CVR
45 mm/yr
41 mm/yr
EHS
Chatham Rise
37 mm/yr
DMO
Pacific Plate
2000 m

shown in Figure 12a, this crustal buckling mechanism could cause oblique extension in the rotating block [*Taymaz et al.*, 1991; *Anderson et al.*, 1993]. Figure 1d is a one-sided migrating hinge model that is characterized by strike-slip faults being translated through a rotational kink boundary which migrates through the rock [e.g., *Little*, 1990]. As in a flexed telephone book, the rotation boundary is not a material discontinuity, and its length need not change. Strike-slip faults terminate eastward into a rotated domain. The model in Figure 1e is a variation of a trellis model that was suggested by *Lamb* [1988]. The last model (Figure 1f) considers crustal blocks that are embedded in a continuously deforming substratum. Motion of elliptical fault blocks depends on their orientation and shape [*Lamb*, 1987].

Deformation that is directly caused by rotation is limited to the ends of blocks: such regions produce few large earthquakes [*McKenzie and Jackson*, 1989] but are accessible to structural studies. The double-slat model (Figure 1c) seems to be an unlikely explanation for rotations in the Northern Marlborough Domain because E striking sinistral-slip faults have not been observed in NE South Island or in the Cook Strait region, nor is there geodetic evidence for the NE oriented principal horizontal shortening direction that is required for buckling. The trellis block model (Figure 1e) can be discounted because NNE striking sinistral faults are uncommon in NE South Island. Instead, dextral strike-slip faults extend into the rotated Northern Marlborough Domain, which is not a rigid block. The viscous substratum concept (Figure 1f) provides a useful dynamical model of fault blocks that are coupled to a flowing mid-lower crust, but it does not help to explain how a series of rigid blocks can deform together as a coherent upper crustal mosaic.

Our structural observations best support a migrating hinge model of fault block rotation (Figure 1d). Evidence for this conclusion includes (1) lack of significant offset of hinge segments 1-3 across the major dextral-slip faults of the Marlborough fault system (despite the Awatere fault having >30 km of finite slip), (2) continuation of the strike-slip faults into the rotated crust east of the rotation boundaries. The Northern Marlborough Domain appears to be rotating as a single block with dimensions larger than the spacing between major strike-slip faults. Eastern ends of faults are passively rotated as part of the Northern Marlborough Domain; and (3) strike-slip faults splay seaward and terminate in or near Cook Strait [*Carter et al.*, 1988; *Barnes et al.*, 1995]. Unlike Figures 1a and 1b, the terminations are not sharp: the late Quaternary slip rate on the Awatere fault drops from ~7 mm/yr to <1.5 mm/yr east of hinge segment 1 [*Little et al.*, in press]; clockwise-rotated, ancestral traces of the Alpine and Awatere faults underlie Cook Strait [*Lewis et al.*, 1994; *Little et al.*, in press]; and the Clarence fault terminates at the southern end of the Awatere basin [*Browne*, 1992b]. Finally, (4) material continuity is maintained across the rotation boundaries, which are expressed as kinks or folds at the kilometer scale (Figure 1d), rather than as faulted discontinuities (Figures 1a and 12b). Although small triangular (transrotational) basins occur in southern California [*Luyendyk and Hornafius*, 1987], worldwide, these appear to be rare along block rotation boundaries. If a migrating-hinge mechanism prevails, then internal block deformation must eliminate gaps along the boundary where faults terminate (Figure 9b). In NE South Island, such deformation includes horsetail fault splaying, local normal faulting and distributed dextral strike-slip faulting (Figures 9a and 9b). The wide distribution of brittle fracture in Torlesse rocks of NE South Island is also consistent with a migrating-hinge model. Densely spaced tensile and shear fractures form a breccia-like mosaic of outcrop- to grain-scale clasts, not only in the rotation zones, but also outside them. Distributed cataclastic flow is likely to be an aseismic deformation mechanism [*Scholz*, 1990].

The migrating hinge model is an oversimplification, and, by itself, cannot fully explain the observed pattern of crustal faulting. For example, the Marlborough strike-slip faults have a small reverse component unlike the cartoon (Figure 1d). Normal faulting in the offshore Wairau basin and Chatham Rise, and oblique-normal faulting at the coastal end of the Awatere fault [*Little*, 1996] imply stretching of the Northern Marlborough Domain. Such extension may indicate that unpinned or double-slat mechanisms operate in offshore parts of the Northern Marlborough Domain (Figures 1a, c). Alternatively, stretching may reflect velocity discontinuities between adjacent, differentially rotating sub-blocks (Figure 9). *Anderson et al.* [1993] suggested a double-slat model to explain crustal extension on the Chatham Rise which caused an M_s 5.8 normal-faulting earthquake (Figure 3). Outer-rise flexure of the down-going Pacific plate is an unlikely cause of offshore extension in the NE South Island [*Anderson and Webb*, 1994].

Paleomagnetic, stratigraphic, and structural data imply that rotation boundaries are not fixed but have shifted SW in the late Neogene, perhaps as the margin lengthened southward. This shift in the locus of rotation avoids a mechanical pitfall associated with all fault block rotation models: that is, the necessity to initiate new generations of faults once rotation of fault blocks has caused them to frictionally lock. Mechanical analyses suggest that <45°-60° of rotation can occur on a single set of faults in the limiting case of extremely low frictional resistance and shallow depths [*Nur et al.*, 1986]. For more realistic effective friction coefficients, maximum rotations of 20°-40° are predicted at typical crustal depths [*Garfunkel*, 1989]. Fixed-boundary fault block rotation models are thus kinematically unstable and self-destroying. Also, the required multiple sets of large faults are generally not recognized in strongly-rotated crustal domains [*Ron et al.*, 1990]. We have presented evidence that post-early Miocene rotations of >100° developed on the South Island by sequential activation of two crustal-scale hinges at different locations. A migrating kink-

Figure 12. (opposite) Schematic reconstruction of Miocene-present plate motions, development of Marlborough fault system, vertical axis rotations in NE South Island, and inferred southward propagation of the Hikurangi subduction zone. Australian plate is held fixed. (a) 20/18 Ma, (b) 10 Ma, (c) 5-0 Ma, and (d) present. Insets contain additional detail of the near-coastal region. Templates of the shoreline and 2000 m isobath are from *Beanland* [1995], who calculated stage poles and velocities from the Antarctic-Pacific and Antarctic-Australia seafloor spreading data of *Mayes et al.* [1990] and *Royer and Sandwell* [1989]. Abbreviations are DMO, Dun Mountain ophiolite belt; EH, Esk Head subterrane; MDFS, Medway fault system; WD, Waihopai extensional domain; WB, Wairau basin; CVR, Central volcanic region. Note contemporaneity of Miocene clockwise rotations on segment 4 to slip on Medway and Flags Creek fault systems (Figure 11b).

band rotation mechanism returns the pattern of particle velocities to an earlier state, thus increasing compatibility with externally imposed plate boundary conditions. Large finite crustal dilations (β; Figures 1a and b) are also avoided.

Implications for Neogene Tectonic Development of New Zealand

Only ~200 km of Cenozoic strike-slip is observed across the major strands of the Marlborough fault system (including the Wairau fault) in contrast to the ~480 km slip that is documented on the central Alpine fault. This discrepancy can be reduced by considering the horizontal motions that are implied by vertical axis rotations in NE South Island. For a given rotation mechanism, observed amounts of finite vertical axis rotation (δ) for a crustal block correspond to shear strains (γ) that drive the rotation (Figure 1). *Dickinson* [1996] has conducted a similar kinematic analysis for the San Andreas system. Dextral shear strains (γ) and displacements (γ x fault spacing) have been calculated from finite clockwise rotations of the coastal Marlborough fault system, as inferred from Torlesse bedding fabric data, for different rotation mechanisms (Table 3). Between the Kekerengu and Wairau faults, these models yield best fit cumulative dextral-slip estimates that vary between 99 and 187 km (at 95% confidence the range is 73-336 km). The migrating hinge model predicts 99 km of rotation-related slip (73-136 km at 95% confidence). With respect to the observed finite offsets, these estimates are of the appropriate order of magnitude. They are also minimum estimates because they exclude (1) ~140 km of throughgoing slip on the Wairau fault [*Mazengarb et al.*, 1993] and (2) any pre-early Miocene plate motion that was absorbed by regional oroclinal bending.

Our data (Figure 7) indicate that the pre-Miocene strike of the Torlesse bedding fabric is NNE, thus the NW to NNE oroclinal deflection of basement fabric between Canterbury and inland Marlborough must be earliest Miocene or older in age.

Table 3. Finite Strains and Cumulative Dextral Slip Predicted for Regions in NE South Island

	Slip/Width				Final/Initial	
Boundary	γ[a]	Range[b]	ΣDextral, km[c]	Range, km[b]	β[d]	Range[b]
			Unpinned Slat Model			
Segment 1	0.7	0.4-1.3	20	12-38	0.8	0.6-1.0
Segment 2	1.5	0.7-3.7	25	12-63	0.6	0.3-0.9
Segment 3	0.9	0.6-1.4	10	7-17	1.0	0.8-1.2
Segment 4 (N)	1.3	0.8-2.1	39	24-63	1.7	1.4-2.4
Segment 4 (S)	2.3	1.2-5.3	68	36-155	2.7	1.8-5.5
Total			(163)	(91-336)		
			Pinned Slat Model			
Segment 1	0.6	0.4-0.8	17	11-23	1.2	1.0-1.7
Segment 2	0.8	0.6-1.1	14	10-19	1.8	1.1-3.9
Segment 3	0.8	0.5-1.2	10	6-14	1.0	0.9-1.6
Segment 4 (N)	1.2	0.7-2.0	36	22-61	0.6	0.4-0.7
Segment 4 (S)	1.7	0.9-3.9	48	25-113	0.4	0.2-0.6
Total			(125)	(74-230)		
			Rolling Hinge Model			
Segment 1	0.6	0.4-0.8	18	12-25	1.0	
Segment 2	1.1	0.7-1.5	18	18-26	1.0	
Segment 3	0.8	0.6-1.2	10	7-14	1.0	
Segment 4 (N)	0.9	0.6-1.2	27	18-36	1.0	
Segment 4 (S)	0.9	0.6-1.2	26	18-35	1.0	
Total			(99)	(73-136)		
			Viscous Substratum Model			
Segment 1	1.2	0.8-1.6	36	24-47		
Segment 2	2.0	1.3-2.6	33	22-45		
Segment 3	1.6	1.1-2.1	19	13-26		
Segment 4 (N)	1.7	1.2-2.2	50	36-65		
Segment 4 (S)	1.7	1.2-2.2	49	34-63		
Total			(187)	(129-246)		

See Figure 3 for rotation boundaries.

a. γ is shear strain, see equations for each block rotation model in Figure 1. Shear strains are converted to cumulative dextral slip by multiplication by fault zone width. Widths used are Wairau-Awatere faults, 30 km; Awatere-Clarence faults, 17 km; Clarence-Kekerengu faults, 12 km. See text for discussion of accommodation of dextral shear.

b. Range is the difference between maximum and minimum values obtained by inserting extreme values of geometric parameters into equations of Figure 1.

c. ΣDextral is cumulative dextral shear across each rotational segment boundary.

d. β is ratio of horizontal crustal stretching perpendicular to fault strike in rotated domain.

The large (~100°) rotations near Kekerengu are not representative of the NE South Island as a whole. *Vickery and Lamb* [1995] attributed near-coastal sites with extreme clockwise rotations of ~120°-140° (BBS, WC1, and WC2) to inferred local shear zones which cause an extra ~20°-40° of rotation relative to adjacent rocks. As they only occur in rocks of Paleogene age, these extreme rotations may instead record the additional effect of an early phase of clockwise rotation that took place between inception of the plate boundary in the Eocene [*Kamp*, 1987b; *Sutherland*, 1995] and propagation of the Alpine fault in the Early Miocene. An early Cenozoic age for at least part of the South Island oroclinal deflection is consistent with 25°±5° of clockwise rotation inferred from paleomagnetic data by *Vickery and Lamb* [1995] for Late Cretaceous mafic dikes at site GS-1 in inland Marlborough (Figures 4 and 7). *Kamp* [1987a] and *Bradshaw* [1989] argue that the South Island orocline is entirely Cretaceous in age.

The limited, near-coastal distribution of Neogene rotations in South Island, New Zealand, sheds light on the nature of the Miocene plate boundary. Our reconstructions (Figure 12) imply that the Marlborough faults have been NE striking strike-slip or transpressional structures since the early Miocene (18 Ma). The faults did not initiate as NW striking, seaward-verging thrusts and have not rotated >100° clockwise since the early Miocene as a stack of thrust nappes that are pinned at their southern end to the Chatham Rise [e.g., *Lamb and Bibby*, 1989; *Vickery and Lamb*, 1995]. Rotations have not been hinged about a boundary near Kaikoura [e.g., *Walcott and Mumme*, 1982; *Lamb and Bibby*, 1989]. Near Kekerengu, only the seaward end of the Clarence fault rotated >100° clockwise in the Miocene (18-8 Ma); a deformation that was transferred southward into shortening across the Flags Creek thrust system (Figure 12a, inset).

Conclusions

Paleomagnetic and structural data indicate that Miocene-present-day vertical axis rotations in NE South Island, New Zealand, are hinged about two kink-like boundaries near the east coast. The eastern hinge accommodated ~50° of early-middle Miocene rotation: it strongly deformed the eastern ends of the Alpine-Wairau and Clarence strike-slip faults, and is inactive. The western boundary has accommodated 30°-50° of post-Pliocene finite clockwise rotation, it defines the western edge of the currently rotating Northern Marlborough Domain, and its location is consistent with velocity fields that have been modeled from geodetic data. West of the Northern Marlborough Domain, rocks have not rotated relative to the Pacific plate since the middle Miocene. Together, the two sets of boundaries define a crustal-scale fold that has accommodated clockwise rotation of a near-vertical bedding fabric in the accretionary basement, thus accounting for >100° of post-Miocene vertical axis rotation on the coast near Kekerengu. Clockwise rotation occurred sequentially on the two sets of boundaries, migrating SW during the late Neogene astride a subduction margin that was also propagating in that direction.

The locked end of the subduction interface near the Chatham Rise is a "pivot" that caused rotation of the Marlborough fault blocks as they were driven clockwise over other rocks of the Pacific plate. Dextral-slip on inland strike-slip faults is transformed seaward across a zone of fault termination into rigid body rotation of near-coastal rocks that are supported at depth by the underlying slab and that are thrust eastward over the Pacific plate. This transfer of motion in the brittle upper crust is expressed by a dying of horizontal slip rate on major strike-slip faults and by clockwise rotation of their deformed eastern ends. The northern edge of the rotating domain is fixed by the original (earliest Miocene) position of the paleo-Alpine fault. Strike-slip faulting in the North Island dextral fault belt accommodates a southward translation of the Hikurangi margin into the northern boundary of the Northern Marlborough Domain in Cook Strait. At the southern end of the rotating domain, near the Chatham Rise, increasingly convergent plate motions in the late Neogene have produced transform fault geometries that are kinematically unstable. As older faults became increasingly transpressive, new, well oriented strike-slip faults formed in undeformed Pacific plate farther to the south and eventually became the principal locus of plate motion. As the margin propagated southward, older, mis-oriented faults began to buckle and rotate.

Less than ~1 km in width, the rotation boundaries are continuous, but are pervasively fractured at the outcrop scale, which suggests deformation by distributed cataclastic flow. Structural data indicate that the best first-order approximation of the hinge rotation mechanism is a migrating hinge similar to that in a flexed telephone book. This allows deformation of the coastal ends of the strike-slip faults, and it allows the hinge boundary to sweep through the rock rather than to coincide with a single material line. A migrating kink-band-like rotation mechanism does not require initiation of multiple fault sets, and it increases compatibility of the rotation-related velocity field with externally imposed plate boundary conditions. Wedge-shaped zones of normal faulting or oblique-divergence occur at velocity discontinuities between differentially rotating domains and on the margin of buckled fault blocks. Within the blocks, horsetail splaying and distributed strike-slip shear are required to accommodate block rotations.

Discrete offsets on major strike-slip faults account for ~200 km of Cenozoic dextral slip through the NE South Island, whereas vertical axis rotations imply an additional >50 km of dextral slip that has been distributed through this region since the Miocene. The orocline on the South Island is pre-early Miocene in age and paleomagnetic data suggest at most 30°-40° of Cenozoic clockwise rotation of this regional structure. The Marlborough faults have been NE striking, transpressional faults since the early Miocene.

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